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Low Scale Orientifold Models

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Bibliography:Reviews

- [arXiv:hep-th/0310001]

Review on orientifold/brane model building (to appear in Physics Reports)

- The effective theory of LSOM

By Coriano, Irges and Kiritsis (to appear this week)

Plan of the presentation

- Neutrino Masses 3 minutes
- Models mLSOM$_B$ and mLSOM$_{B'}$ 2 minutes
- The fate of anomalous U(1)'s 2 minutes
- The fate of anomalous U(1)'s:continued 4 minutes
- Anomalous U(1) masses 3 minutes
- Z-Z' mixing 3 minutes
- The Higgs Sector 2 minutes
- Axions and Axi-Higgs 3 minutes
- The bulk U(1)' 3 minutes
- SURGEON'S WARNING !!!!! 2 minutes

The particle Zoo in Orientifolds

D-brane sector

Except the SM particles :

• Extra massive U(1) which are "anomalous". Their masses can be from M_s to $<< M_s$. They are unavoidable.

• Higgs doublets Can be 2, 4, 6, ... depending on the model.

• Superpartners. Masses depended on susy breaking and M_s. Very model dependent

• Hidden matter and interactions. Although there are string examples with none, they are useful for breaking supersymmetry and potentially confining fractional charges.

• Brane KK modes. When $M_s \sim M_P$ they have masses of order M_s relevant only for precision threshold calculations. When $M_s \sim TeV$, they can be produced in LHC, the lightness of neutrinos can be associated with large dimensions and there is non-trivial mixing with them.

Antoniadis+Kiritsis+Rizos+Tomaras

Matias+Burgess

• Brane stringy modes. $M_s \sim M_P$, relevant for thresholds. M_s ~TeV could be produced, give measurable tree and loop corrections to processes.

The bulk sector (closed strings)

- 4D Gravitons

- Other “low lying” vectors, scalars and fermions. They will be heavy if closed-string moduli are stabilized appropriately. Perturbative Brane matter is uncharged under bulk vectors (RR) except for KK+Winding states.

- Bulk KK states.Same comments as on branes: can be produced when M_s very low.

- Bulk stringy states. Same comments as on branes: can be produced when M_s very low.

Low string scale vacua

- Define benchmark LEEFTs that parameterize effectively the low energy physics.

There are two options here:

♣ Since susy breaks at M_s, in a class of models, the anomalous (massive) U(1)s will be substantially lighter that standard superpartners.

This motivates the simplest "benchmark" LEEFT: mLSOM$_a$

It is characterized by:

(1) The particle content: SM particles, right-handed neutrinos, 2 Higgses, 3 anomalous U(1)'s and their associated bulk axions, and the light KK modes, coming from the two large dimensions which play an important role in neutrino mixing.

(2) An index taking four values and running over different charge structures of the SM particles under the extra U(1) symmetries.

• The explicit mLSOM$_a$ effective action is being developed

Coriano+Irges+Kiritsis to appear

Most of the work both on constraints and new effects at LHC remains to be done

♠ The second "benchmark" LEEFT: sLSOM$_a$. Here the superpartners are kept, as well as the soft susy breaking terms.
This is an extended version of the MSSM, including 3 extra anomalous U(1) multiplets plus KK states.

Writing and analysing this LEFFT is an open problem.

There are some theoretical issues that do not occur in MSSM and need some clarification. They are associated with

• The supersymmetric couplings of the anomalous U(1) multiplets in the globally supersymmetric limit

• The analogue of soft terms for anomalous U(1)'s (usual susy analysis does not apply here.

Important issues in mLSOM

$$(M_s \sim 1 - 100 TeV)$$

- Here, two out of six dimensions have sub-millimeter size

♣Since the "unification" scale is low, GOOD lepton number and baryon number symmetries are CRUCIAL.

Lepton and baryon number will be gauged (anomalous) symmetries

♠ We utilize the existence of large dimensions to produce naturally light neutrino masses.

♡ Families can be generated from multiple brane intersections

Models mLSOM$_A$ and mLSOM$_{A'}$

Gauge group: $U(3) \times U(2) \times U(1) \times U(1)'$

SM particle	$U(1)_3$	$U(1)_2$	$U(1)$	$U(1)'$
$Q(\mathbf{3}, \mathbf{2}, +\frac{1}{6})$	$+1$	-1	0	0
$u^c(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$	-1	0	-1	0
$d^c(\bar{\mathbf{3}}, \mathbf{1}, +\frac{1}{3})$	-1	0	0	-1
$L\ (\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	0	$+1$	0	-1
$e^c(\mathbf{1}, \mathbf{1}, +1)$	0	0(2)	1(0)	1(0)
$H_u\ (\mathbf{1}, \mathbf{2}, +\frac{1}{2})$	0	1	1	0
$H_d\ (\mathbf{1}, \mathbf{2}, +\frac{1}{2})$	0	-1	0	-1
$\nu^c(\mathbf{1}, \mathbf{1}, 0)$	0	0	0	± 2

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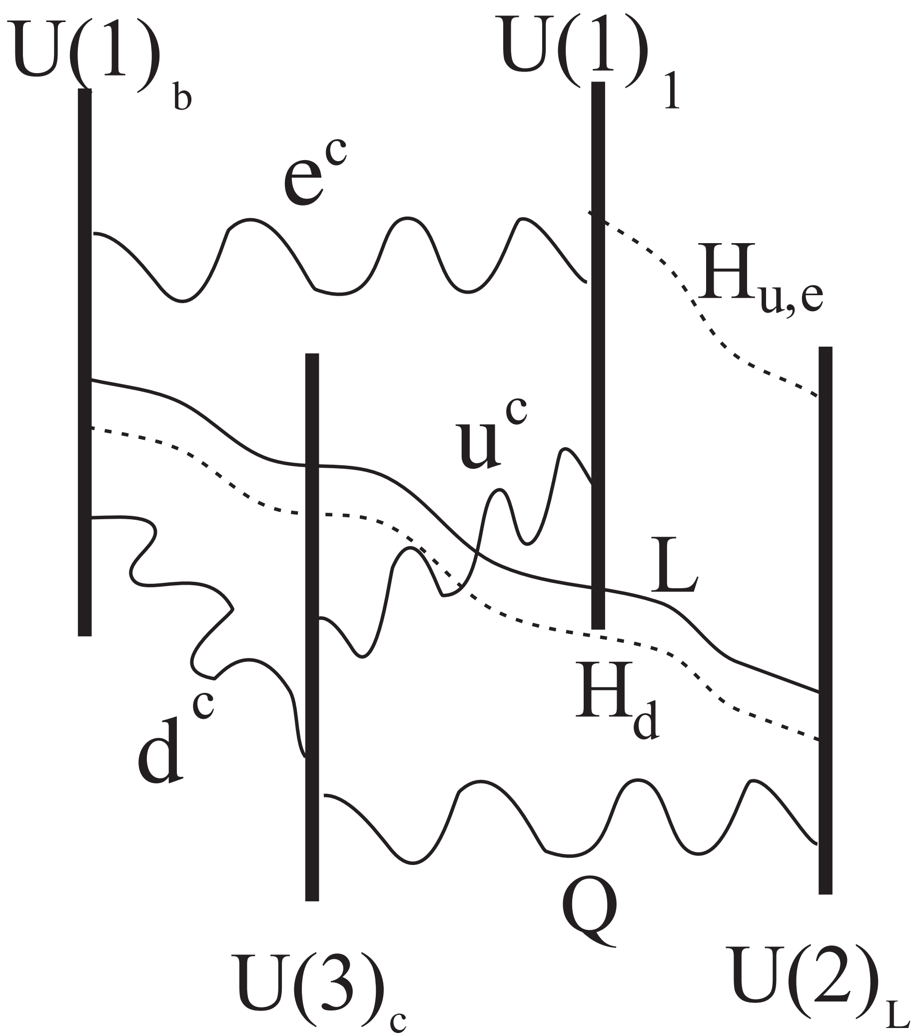
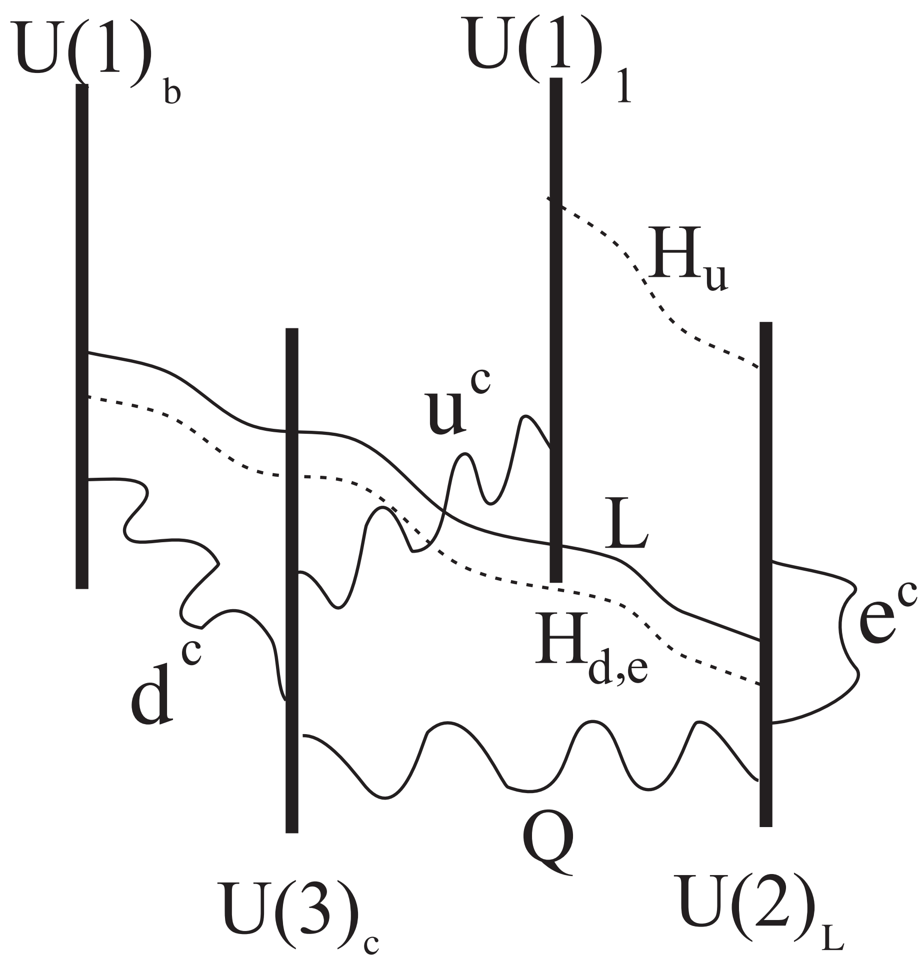


$U(1)_b$
$U(1)_l$
e^c
$H_{u,e}$
u^c
L
H_d
d^c
Q
$U(3)_c$
$U(2)_L$



$U(1)_b$
$U(1)_l$
H_u
u^c
L
e^c
$H_{d,e}$
d^c
Q
$U(3)_c$
$U(2)_L$

Models mLSOM$_A$ and mLSOM$_{A'}$: continued

Hypercharge:

$$Y = -\frac{1}{3}Q_3 - \frac{1}{2}Q_2 + Q_1$$

Global symmetries:

$$\text{Baryon Number} \quad B = \frac{1}{3}Q_3$$

$$\text{Lepton Number} \quad L = \frac{1}{2}(Q_3 + Q_2 - Q_1 - Q_1')$$

$$\text{Peccei} - \text{Quinn} \quad PQ = -\frac{1}{2}(Q_3 - Q_2 - 3Q_1 - 3Q_1')$$

All U(1)'s except Y are "anomalous" and therefore massive. All except PQ remain as good global symmetries.

Parameters of mLSOM

Apart from the usual SM parameters we have

• Potential new parameters in the Higgs potential (maximum 5 more are allowed by the gauge symmetry bur are seriously constrained)

• The UV mass matrix of the U(1)s: Y and 3 anomalous ones. Y corresponds to a zero eigenvalue and a known eigenvector. We are left with three non-zero eigenvalues and three (real) mixing angles.

• The radii of the large and small compact dimensions

• In the neutrino sector there are two possibilities:

(a) Mixing with one flavor of bulk neutrino, and its KK states (fewer parameters than the SM)

(b) Mixing with three flavors of bulk neutrinos (as in the usual extension of SM)

New particles of mLSOM

- The new particles (beyond the SM) here are:

(a) The 3 massive anomalous U(1)s $\to$ Z's

(b) The extra particles coming from the Higgs sector plus bulk axions. They are the same as in the MSSM, but without the usual supersymmetric constraints on the Higgs potential.

(c) KK modes of particles sensitive to the large dimensions (R-neutrinos, gravitons, U(1)' gauge bosons)

Other implications

• The neutrinos come from large dimensions. Their mixing with KK descendants with

$$\frac{1}{R} \simeq 10 - 100\ \frac{M_s}{M_P} \sim 10^{-5} - 10^{-2}\ eV$$

might be observable. This has been partly analyzed , but the main work remains still not done.

• The KK states of the bulk fields (graviton et al.) are those of two large extra dimensions with all the known implications for LHC.

• One of the Z' is unusual. This is the one mainly coming from the U(1)'. Its coupling is almost of gravitational strength

$$g_1' \sim \frac{M_s}{M_P} \sim 10^{-15}$$

Its mass must be larger than 50 MeV, to avoid astrophysical constraints. It has graviton-like KK states.

• There are always the usual Susy related neutralinos. Their masses vary depending on the ground state.

To summarize: the weakly coupled particles are neutralinos, the U(1)' boson and KK descendants of bulk neutrinos.

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The End

Gauge couplings

The hypercharge gauge coupling is given by

$$\frac{1}{g_Y^2} = \frac{6k_3^2}{g_3^2} + \frac{4k_2^2}{g_2^2} + \frac{2k_1^2}{g_1^2} + \frac{2k_1'^2}{g_1'^2} \quad , \quad \frac{1}{g_i^2} = \frac{V_i}{g_s}$$

k_1' must be zero because $V_1' >> 1$ so that $g_1' << 1$.

We may now determine k_i and the possible charge assignments by asking:

- The hypercharge values of the SM particles are correct (This is anomaly freedom up to an overall scale).

- Lepton number is one of the gauge U(1) symmetries

- That the gauge couplings fit the data with a low M_s.

This selects two models A, B, each coming in two slightly different versions (A',B').

We will call them minimal Low Scale Orientifolds (mLSO). We will labelled them as $mLSO_{A,A',B,B'}$ for simplicity.

Quark and Lepton masses

For the 3rd generation the structure of masses is:

$$M_{\text{model A}'} = \lambda_u\, Q\, u^c\, H_u + \lambda_d\, Q\, d^c\, H_d^\dagger + \lambda_e\, L\, e^c\, H_d^\dagger + \lambda_\nu\, L\, H_d\, \nu_R$$

(tree level, trivial moduli dependence and a particular brane configuration D_5-D_5-D_5)

$$\lambda_u = \lambda_e = \sqrt{2} g_2 \ , \quad \lambda_d = \sqrt{2 g_s} \ , \quad \lambda_\nu = \sqrt{2} g_1' << 1 \, .$$

Fitting $m_b \simeq 4$ GeV we get

$$m_t \simeq 162 \quad \text{GeV} \quad \text{(not so bad!)}$$

$$\frac{m_b}{m_\tau} = \frac{\sqrt{g_s}}{g_2} \simeq \frac{g_3}{g_2} \Rightarrow m_\tau(M_s) = 1.75 \quad \text{GeV}$$

This is not very far from the measured value $m_\tau(M_Z) = 1.46$ GeV and in fact running gets it closer.

The neutrino masses are in the range $10^{-5} = 10^{-3}$ eV.

For the model A

$$M_{\text{model A}} = \lambda_u\, Q\, u^c\, H_u + \lambda_d\, Q\, d^c\, H_d^\dagger + \lambda_e\, L\, e^c\, H_u^\dagger + \lambda_\nu\, L\, H_d\, \nu_R$$

Again the top comes out right.

But $m_\tau \sim m_t$ which is unrealistic. Several ways out:

(a) to have $\lambda_e = 0$ at tree level so that the τ mass is generated from higher order terms.

(b) Non-rivial moduli alter the values of Yukawa's

Neutrino Masses

Consider the left-handed neutrino ν_L being a fluctuation of a 3-brane. Consider also a right-handed neutrino ν_R being a fluctuation of a (p+3)-brane wrapping a p-dimensional internal large volume V_p.

Dienes+Dudas+Gherghetta

We have the following action

$$S \sim \int d^{p+4}x \; (\; \bar\nu_R \; \partial\!\!\!/ \; \nu_R \;) + g \int d^4x \; (\; \bar\nu_R \; H \; \nu_L \;)$$

which upon compactification and symmetry breaking becomes

$$S \to \int d^3x \;\; [V_p \; (\; \bar\nu_R \; \partial\!\!\!/ \; \nu_R \;) + m \; \bar\nu_R \; \nu_L]$$

$m = g \; v \sim M_Z$ Normalizing kinetic terms by $\nu_R \to \nu_R/\sqrt{V_p}$ we obtain

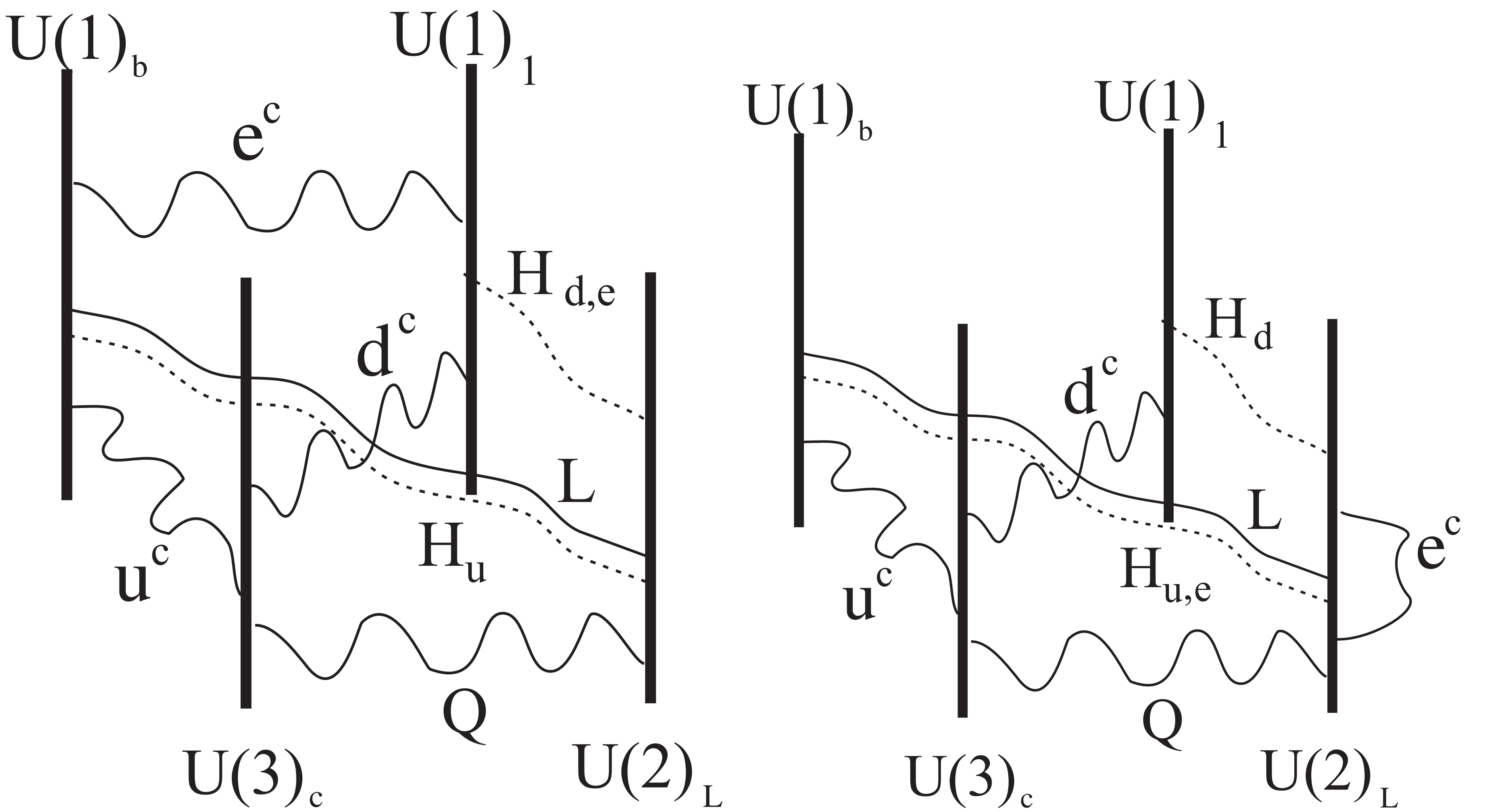
$$S \sim \int d^3x \; \left[\bar\nu_R \; \partial\!\!\!/ \; \nu_R + \frac{m}{\sqrt{V_p}} \; \bar\nu_R \; \nu_L \right]$$

$$m_\nu \sim \frac{M_Z}{\sqrt{V_p}} \sim M_Z \left(\frac{M_s}{M_P}\right) \sqrt{g_s} \; g_U$$

This gives $m_\nu \sim 10^{-6} - 10^{-3}$ eV.

Models mLSOM$_B$ and mLSOM$_{B'}$

SM particle	$U(1)_3$	$U(1)_2$	$U(1)$	$U(1)'$
$Q(\mathbf{3},\mathbf{2},+\frac{1}{6})$	$+1$	-1	0	0
$u^c(\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	-1	0	0	1
$d^c(\bar{\mathbf{3}},\mathbf{1},+\frac{1}{3})$	-1	0	1	0
$L\ (\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$+1$	0	-1
$e^c(\mathbf{1},\mathbf{1},+1)$	0	0(2)	1(0)	1(0)
$H_u\ (\mathbf{1},\mathbf{2},+\frac{1}{2})$	0	-1	0	-1
$H_d\ (\mathbf{1},\mathbf{2},+\frac{1}{2})$	0	1	1	0
$\nu^c(\mathbf{1},\mathbf{1},0)$	0	0	0	± 2


U(1)b
U(1)1
e^c
H d,e
d^c
L
H_u
u^c
Q
U(3)c
U(2)L
U(1)b
U(1)1
H d
d^c
L
e^c
H u,e
u^c
Q
U(3)c
U(2)L

Models mSLO$_B$ and mSLO$_{B'}$

Hypercharge:

$$Y = \frac{2}{3}Q_3 - \frac{1}{2}Q_2 + Q_1$$

Gauge couplings and string scale:

$$V_1 = V_3 \quad , \quad M_s \sim 7 \quad TeV$$

$$3V_1 = V_2 + V_3 \quad , \quad M_s \sim 3.5 \quad TeV$$

Global symmetries:

$$\text{Baryon Number} \quad B = \frac{1}{3}Q_3$$

$$\text{Lepton Number} \quad L = -\frac{1}{2}(Q_3 - Q_2 + Q_1 + Q'_1)$$

$$\text{Peccei} - \text{Quinn} \quad PQ = \frac{1}{2}(-Q_3 + 3Q_2 + Q_1 + Q'_1)$$

All U(1)'s except Y are "anomalous" and therefore massive. All except PQ remain as good global symmetries.

The fate of anomalous U(1)s

♢ All U(1)s except Y have anomalies: mixed abelian-non-abelian anomalies with SU(2) and SU(3) and (abelian)^3 anomalies.

♣ These anomalies are cancelled by the GS mechanism.

The gauge boson is now massive
and the associated gauge symmetry broken.

♠ For symmetric values of bulk moduli the global U(1) symmetry remains intact.

♡ The global symmetry is broken however beyond perturbation theory by instantons. In the case of Baryon and Lepton number, these are the SU(2) instantons, and such a rate (calculated by 't Hooft) is VERY small. This need not be the case for the PQ symmetry.

To summarize, the remaining global U(1) symmetry remains a good symmetry if the instanton effects are small and the bulk moduli have special values.

The fate of anomalous U(1)s:continued

♣ Example: A U(1) gauge symmetry that has a mixed triangle anomaly (e.g. $\zeta = Tr[QT^aT^a] \neq 0$) The one-loop fermionic determinant induces a non-invariance to U(1) gauge transformations

$$A_\mu \to A_\mu + \partial_\mu \epsilon \quad , \quad \delta L_{1-\text{loop}} = \epsilon\ \zeta\ Tr[G \wedge G]$$

This is cancelled by a non-invariance of the classical (tree level action).

$$\mathcal{L}_{\text{class}} \sim -\frac{1}{4g^2} F_{\mu\nu}^2 + \frac{M^2}{2}(\partial_\mu a + A_\mu)^2 + \zeta\ a\ Tr[G \wedge G]$$

The axion now transforms

$$a \to a - \epsilon \quad , \quad \mathcal{L}_{\text{class}} \to \mathcal{L}_{\text{class}} - \zeta\ \epsilon\ Tr[G \wedge G]$$

and the anomaly is cancelled.

- The D-term-like potential is of the form

$$V \sim \left(s + \sum_i q_i |\phi_i|^2 \right)^2$$

where s is a bulk modulus. In SUSY Theories it is the chiral partner of the axion "eaten up" by the anomalous U(1) gauge boson. If $< s >= 0$, the global U(1) symmetry remains intact.

Anomalous U(1) masses

There are two sources for the masses of anomalous U(1)s:

• The UV mass-term responsible for anomaly cancellation

$$L_{UV} \sim \frac{1}{2} M^2 (\partial_\mu a + A_\mu)^2$$

This is computable only in string theory. It turns out that

$$M \sim g \frac{M_s}{\sqrt{V}}$$

Depending on V it can be $\sim M_s$ or $<< M_s$ (unlike the heterotic string).

• contributions from spontaneous symmetry breaking. The standard Higgses when they get vevs they break also the U(1) symmetries In total:

$$M \simeq \sqrt{M^2 + g^2 v^2} \simeq \sqrt{M^2 + M_Z^2}$$

In this class of models, such Z's are generic, their low energy couplings fixed by charges and anomalies and only M depends on UV physics.

Z-Z' mixing

After the Higgs mechanism, the three mass eigenstates, the photon A, the Z^0, and the Z'-bosons, are specific linear combinations of W^3, Y and A^i gauge bosons. Inversely

$$\begin{pmatrix} W^3 \\ Y \\ A^i \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & \mathbf{c_{13}} \\ c_{21} & c_{22} & \mathbf{c_{23}} \\ \mathbf{c_{31}} & \mathbf{c_{32}} & c_{33} \end{pmatrix} \begin{pmatrix} A_\gamma \\ Z^0 \\ Z' \end{pmatrix}$$

We have

$$c_{11}, c_{12}, c_{21}, c_{22}, c_{33} \sim \mathcal{O}(1) \quad , \quad c_{13}, c_{23}, c_{31}, c_{32} \sim \mathcal{O}\left(\frac{M_Z}{M_s}\right) < 10^{-4}$$

The ρ-parameter, $\rho = \frac{M_W^2}{M_Z^2 \sin\theta_W}$, is no more equal to the standard model value

$$\frac{\Delta\rho}{\rho_0} \sim \frac{M_Z}{M_s} < 6 \times 10^{-4}$$

and there are small modifications of the Z^0 couplings to the fermions.

The Higgs sector

Although the low energy spectrum is non-supersymmetric, we have a Higgs sector reminiscent of the MSSM.

Here a priori more general terms are allowed.

• If the breaking of supersymmetry is due to internal magnetic fields, then all quartic terms can a priori appear at tree level. This changes the bounds on the lightest Higgses.

• If supersymmetry breaks via the branes sitting at singularities, then the tree-level terms in the potential are the usual supersymmetric D-terms that align the vev's of the Higgses. However, as in the SM , at loop level all terms will be generated.

• The PQ symmetry is broken by the potential. This is important in order to give a mass to the associated PQ axion. The dimension-2 term with this property is the μ-term of the MSSM

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad H_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}$$

$$V_{PQ}(H_u, H_d) = \sum_{a=u,d} \left(\mu_a^2 H_a^\dagger H_a + \lambda_{aa} (H_a^\dagger H_a)^2 \right) - 2\lambda_{ud} (H_u^\dagger H_u)(H_d^\dagger H_d) + 2\lambda'_{ud} |H_u^T \tau_2 H_d|^2 .$$

$$V_{PQb} = B\,(H_u^\dagger H_d e^{-i \sum_I (q_u^I - q_d^I) \frac{a'_I}{M_I}}) + \lambda_1 (H_u^\dagger H_d e^{-i \sum_I (q_u^I - q_d^I) \frac{a'_I}{M_I}})^2$$
$$+ \lambda_2 (H_u^\dagger H_u)(H_u^\dagger H_d e^{-i \sum_I (q_u^I - q_d^I) \frac{a'_I}{M_I}}) + \lambda_3 (H_d^\dagger H_d)(H_u^\dagger H_d e^{-i \sum_I (q_u^I - q_d^I) \frac{a'_I}{M_I}}) + c.c.$$

Correspondence with MSSM parameters:

$$\mu_{u,d} \to \mu_{1,2} \quad , \quad \lambda_{uu} = \lambda_{dd} = -\frac{1}{2}\lambda_{ud} = \frac{1}{8}(g_1^2 + g_2^2) \quad , \quad \lambda'_{ud} = \frac{g_2^2}{4} \quad , \quad \lambda_{1,2,3} = 0$$

Axions and Axi-Higgs

To indicate the problem consider

$$S=-\frac{1}{4g^2}F_{\mu\nu}^2-\frac{1}{2}(k\partial_\mu a+M\ A_\mu)^2+\mathcal{A}_i\ aTr[G_i\wedge G_i]-\frac{1}{2}|\partial_\mu H+ie\ A_\mu\ H|^2+V(|H|)+\gamma\ H\ \psi\bar{\psi}$$

where $\mathcal{A}_i$ is the mixed anomaly $Tr[Q\ T_i^aT_i^a]$. Diagonalizing and gauge fixing we obtain

$$S=-\frac{1}{4g^2}F_{\mu\nu}^2-\frac{M^2+e^2v^2}{2}\ A_\mu^2-\frac{1}{2}(\partial_\mu\chi)^2-\frac{\mathcal{A}_iev}{k\sqrt{M^2+e^2v^2}}\ \chi\ Tr[G_i\wedge G_i]+\gamma v\ e^{\frac{iM\ \chi}{v\sqrt{M^2+e^2v^2}}}\ \psi\bar{\psi}$$

Putting the anomaly into the fermion phase the linearized Yukawa coupling of the axion χ to the fermions is

$$\gamma_\psi\simeq\frac{m_\psi M}{v\sqrt{M^2+e^2v^2}}+\frac{\mathcal{A}_i\ m_\psi\ ev}{k\sqrt{M^2+e^2v^2}}$$

$$\frac{1}{g^2}=\frac{V_cV_A}{g_s}\quad,\quad M^2=\frac{V_c}{V_a}M_s^2\quad,\quad k^2=\frac{V_cV_a}{g_s^2}\quad,\quad \mathcal{A}_i\sim\frac{a_i}{M_s}$$

For $M>>M_Z$ the first term is important for heavy quarks.

For $M<<M_Z$, both factors can be small, but then the Z' must be unobservable. This will happen for $g<<1$ which needs four large dimensions, and then there is trouble with supernovae energy loss.

The bulk U(1)'

We have seen that U(1)' wraps the two large dimensions. Therefore its gauge boson has finely spaced KK states, like the KK gravitons. The only other SM filed that feels the large dimensions is the right-handed neutrino

An estimate of its coupling is

$$g^2 \simeq (4\pi\alpha_{\text{strong}})\frac{M_s^2}{M_P^2} \sim 5\times 10^{-31}$$

if its UV mass is $M \sim M_s$ then its physical mass is

$$M_{\text{phys}} = gM_s \sim 5\times 10^{-3} \quad \text{eV}$$

Although this is allowed by table-top experiments it is excluded by Supernova data because

$$\frac{P_A}{P_g} \sim \frac{1}{g_s}\left(\frac{M_s}{T}\right)^2 \sim 10^8 - 10^{10}$$

Therefore, this gauge boson must take a mass from an N=2 sector.

$$\frac{1}{g^2} = \frac{V_c V_A}{g_s} \quad , \quad M^2 = \frac{V_c}{V_a}M_s^2 \quad ,$$

This corresponds to $V_c >> 1$, $V_a, V_A \sim 1$ which would imply $M_{\text{phys}} \sim M_s$ which is acceptable.

SURGEON'S WARNING !!!!!

♣ There are orientifold models with light spectrum only the one I presented (SM, 2 Higgses, right-handed neutrinos plus extra U(1)s)

♣ There are orientifold models with large compactification manifold, as advocated here.

♠ There are orientifold models where SUSY is broken at the String scale without closed or (unrealistic) open string tachyons.

♠ There are orientifold models where SUSY is broken completely and which are in equilibrium at tree level (cancelled tadpoles → cancellation of UV divergences in open theory)

♢ There are orientifold models, with all moduli (including the dilaton) are stabilized.

♡ There are orientifold models, with no fractional charged particles.

♡ There are orientifold models with no SM exotics.

There are combinations of the above.

HOWEVER, THERE IS NO STRAIGHT

(♣♢♠♡)

YET!