The supersymmetric standard model from the $\mathbb{Z}_6'$ orientifold?

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Outline

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Background

- Open strings that begin and end on a stack a of N_a D6-branes wrapping a 3-cycle of $T^6 = T_1^2 \otimes T_2^2 \otimes T_3^2$ give the (massless) gauge bosons of $U(N_a) = U(1)_a \otimes SU(N_a)$.
- At the intersections of two stacks a and b there is chiral matter in the bi-fundamental $(\mathbf{N}_a, \overline{\mathbf{N}}_b)$ representation of $U(N_a) \otimes U(N_b)$, where $\mathbf{N}_a$ and $\overline{\mathbf{N}}_b$ respectively have charges $Q_a = +1$ and $Q_b = -1$ with respect to $U(1)_a$ and $U(1)_b$. To get the standard model, we start with $N_a = 3$ and $N_b = 2$ and then arrange that there are $a \cap b = 3$ intersections. This will give 3 quark doublets $Q_L = (\mathbf{3}, \overline{\mathbf{2}})$.
- However, $3(\mathbf{3}, \overline{\mathbf{2}})$ has $Q_b = -9$. The only other (chiral) doublets in the standard model are the 3 lepton doublets $L = (\mathbf{1}, \mathbf{2})$. If we arrange that there are $b \cap c = 3$ such intersections, there would remain $Q_b = 6$ units of doublet charge to be found from other sources to cancel Q_b overall.

- This requires additional (vector-like) non-standard model matter.
- If instead we wrap an “orientifold” T^6/Ω, where Ω is the world-sheet parity operator then at the intersections of a and the orientifold image b' of b the chiral matter is in the $(\mathbf{N}_a, \mathbf{N}_b) = (\mathbf{3}, \mathbf{2})$ representation. Then $2(\mathbf{3}, \overline{\mathbf{2}}) + 1(\mathbf{3}, \mathbf{2})$ has $Q_b = -3$ which *can* be cancelled by 3 lepton doublets.
- To get *just* the standard model we require that $(a \cap b, a \cap b') = \pm(\underline{2, 1})$.

Ibáñez, Marchesano & Rabadán

- D6-branes wrapping 3-cycles of T^6/Ω generally give a non-supersymmetric spectrum. This requires a low (TeV-scale) unification/string scale to avoid the hierarchy problem. Such low-scale models have unacceptable levels of flavour changing neutral currents induced by world-sheet instantons.

Abel, Lebedev & Santiago

- Non-susy theories generally have uncancelled NSNS tadpoles, which reflect the instability of the complex structure moduli of T^6. We can stabilise (some of) these moduli using an “orbifold” T^6/P. We shall be concerned only with the point groups $P = \mathbb{Z}_6$ and $\mathbb{Z}_6'$ We shall study orientifolds in which the orbifold is quotiented with the world-sheet parity operator Ω.
- If the embedding of P is supersymmetric, then RR tadpole cancellation also ensures NSNS tadpole cancellation too.

Cvetič, Shiu & Uranga

$\mathbb{Z}_6$ orientifold

- We may use a complex coordinate $z_k \ (k = 1, 2, 3)$ in each torus T^2_k. The point group generator acts on these as $\theta z_k = e^{2\pi i v_k} z_k$. For the $\mathbb{Z}_6$ orbifold, $\mathbf{v} = \frac{1}{6}(1, 1, -2)$. The action of θ must be an automorphism of the lattice, so we may use an $SU(3)$ root lattice in each of the tori T^2_k.
- The embedding $\mathcal{R}$ of Ω acts as $\mathcal{R} z_k = \overline{z}_k$ and for this too to be an automorphism (each) lattice must be in either the **A** or **B** configuration. Then there are 6 essentially different lattices to consider.
- Since $b_3(T^6/\mathbb{Z}_6) = 2$ there are 2 independent (invariant, untwisted) bulk 3-cycles $\rho_{1,2}$. The only non-zero intersection is even: $\rho_1 \cap \rho_2 = -2$.
- To get odd intersection numbers you have to use fractional branes

$$a = \frac{1}{2}\left[\Pi_a^{\rm bulk} + \Pi_a^{\rm exceptional}\right]$$

where $\Pi_a^{\rm exceptional}$ consists of a collapsed 2-cycle stuck at a ($\mathbb{Z}_2$) fixed point in $T_1^2 \otimes T_2^2$ times a 1-cycle in T_3^2.

- They occur only in the θ^3 twisted sector. There are 10 independent exceptional cycles $\epsilon_i, \tilde{\epsilon}_i, \ (i = 1, 2 ... 5)$ with non-zero intersection numbers $\epsilon_i \circ \tilde{\epsilon}_j = -2\delta_{ij}$. The pairs of fixed points to be used are determined by the wrapping numbers in $T^2_{1,2}$ of the bulk part.

- On the $\mathbb{Z}_6$ orientifold, there is just one $\mathcal{R}$-invariant combination for each lattice, and all supersymmetric stacks are automatically $\mathcal{R}$-invariant.

- In orientifolds there is also chiral matter on the branes (as well as gauge particles). The matter is in the symmetric representation $\mathbf{S}_a = (\mathbf{N}_a \times \mathbf{N}_a)_{\rm symm}$ and the antisymmetric representation $\mathbf{A}_a = (\mathbf{N}_a \times \mathbf{N}_a)_{\rm antisymm}$ of $U(N_a)$. Now, $\mathbf{S}_a = \mathbf{6}$ for $N_a = 3$ and $\mathbf{S}_b = \mathbf{3}$ for $N_b = 2$ and both are excluded phenomenologically.

- Orientifolding induces topological defects, O6-planes, (which are sources of RR charge). If a is supersymmetric, then $\Pi_a^{\rm bulk} \propto \Pi_{\rm O6}$ and $a \cap \Pi_{\rm O6} = 0$. Consequently $\#(\mathbf{S}_a) = \#(\mathbf{A}_a) = a \cap a'$, and likewise for b. To avoid symmetric, and hence also antisymmetric, representations of the (non-abelian) gauge groups we require that $a \cap a' = 0 = b \cap b'$. Honecker & Ott have shown that it is then impossible for $(a \cap b, a \cap b') = \pm(\underline{2, 1})$.

$\mathbb{Z}_6'$ orientifold

- Can we get the required intersection numbers using the $\mathbb{Z}_6'$ orientifold? The twist vector is $\mathbf{v} = \frac{1}{6}(1, 2, -3)$. On $T^2_{1,2}$ the point group can again be realised using an $SU(3)$ root lattice. P acts as a reflection on T^2_3, so the complex structure U_3 is unconstrained. There are still two ($\mathcal{R}$-invariant) orientations of T^2_3: $\mathrm{Re}\, U_3 = 0$ in **A**, and $\mathrm{Re}\, U_3 = \frac{1}{2}$ in **B**, but $\mathrm{Im}\, U_3$ is arbitrary.
- $b_3(T^6/\mathbb{Z}_6') = 4$, so there are 4 independent (invariant, untwisted) bulk 3-cycles $\rho_{1,2,3,4}$. The intersection numbers $\rho_i \cap \rho_j$ are even, so again we must use fractional branes to get the standard model.
- Supersymmetry constrains Π_a^{bulk}. On the **AAB**-lattice, for example,

$$\sqrt{3}(2A_3 + A_6) = (A_6 - 2A_4)2\,\mathrm{Im}\, U_3$$
$$4A_1 - 2A_3 + 2A_4 - A_6 > 2\sqrt{3}A_6\,\mathrm{Im}\, U_3$$

- There are two independent $\mathcal{R}$-invariant combinations for each lattice. On the **AAB**-lattice

$$2A_3 + A_6 = 0 = A_6 - 2A_4$$

Both are supersymmetric (provided Im U_3 has the correct sign). But in this case there are supersymmetric combinations that are not $\mathcal{R}$-invariant.

- Exceptional cycles occur in the $\theta^{2,4}$ and θ^3 twisted sectors. The latter generates 8 independent cycles $\epsilon_i, \tilde{\epsilon}_i, \ (i = 1, 4, 5, 6)$ with $\epsilon_i \cap \tilde{\epsilon}_j = -2\delta_{ij}$. Only this sector looks rich enough to generate the required intersection numbers.

- We must exclude symmetric matter but not necessarily antisymmetric matter. $\mathbf{A}_a = (\mathbf{3} \times \mathbf{3})_{\text{antisymm}} = \overline{\mathbf{3}} \sim q_L^c$ could be quark singlet states, and $\mathbf{A}_b = (\mathbf{2} \times \mathbf{2})_{\text{antisymm}} = \mathbf{1} \sim \ell^c$ could be lepton singlet states. However, we do not want more than three right-chiral quarks q_L^c or lepton singlets ℓ_L^c with the same hypercharge. So we also require that $\#(A_a) \leq 3$ and $\#(A_b) \leq 3$.

- We find that we **can** find supersymmetric stacks a and b satisfying $(a \cap b, a \cap b') = \pm(\underline{2, 1})$ (and the other conditions) In all cases there is neither symmetric nor antisymmetric matter on one of the stacks. Whether or not there is any antisymmetric matter on the other stack depends upon the lattice. We have examples of both cases.

- Supersymmetry fixes the complex structure $\mathrm{Im}\, U_3$ on T_3^2.

Summary & conclusions

The most direct route to just the (supersymmetric) standard model is to find supersymmetric stacks a, b with $N_a = 3$ and $N_b = 2$, with no symmetric matter, not too much antisymmetric matter, and $(a \cap b, a \cap b') = \pm(2, 1)$ or $\pm(1, 2)$. This cannot be done using the $\mathbb{Z}_6$ orientifold.

It can be done using the $\mathbb{Z}_6'$ orientifold. By adding further branes $c, d, \ldots$ with $N_{c,d,\ldots} = 1$ it may be possible to construct a model with just the spectrum of the (supersymmetric) standard model, consistent with tadpole cancellation.

Different lattices give different solutions and numbers of solutions. Some have q_L^c or ℓ_L^c states as antisymmetric matter on one of the stacks.

We could instead use the G_2 lattice on one or more of the tori T^2_k (in both the $\mathbb{Z}_6'$ and the $\mathbb{Z}_6$ cases).

The Kähler moduli and dilaton could perhaps be stabilised using flux compactifications and the "rigid corset" of Cámara, Font & Ibáñez .

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