String Phenomenology
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"Getting the Standard Model from free-field Orientifolds"

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Bibliography

• Presentation based on joint ongoing work with :

Bert Schellekens and M. Tsulaia .

Michael Lennek and Bert Schellekens

.

Draws also on previous work:

• Anastasopoulos, Dijkstra, Kiritsis and Schellekens **hep-th/0605226**

Why is string "Model Building" difficult?

♠In gauge theories, model building is VERY modular. Most important features are decided quickly by picking the gauge group, spectrum (quantum numbers)and global symmetries.

♣In string theory the construction of vacua is quasi-geometrical (In general worse: relying on CFT)

- No direct way of choosing the gauge group or the spectrum.
- No direct way of choosing the effective potential.
- The analysis of a single ground state is a major project computationally

towards SM vacua

• Original approach: TOP-DOWN Driven by hopes of uniqueness. Such hopes seem very dim, these days.

• Alternative approach: BOTTOM-UP

Antoniadis+Kiritsis+Tomaras

Aldazabal+Ibanez+Quevedo+Uranga

• Can be implemented in orientifolds (vacua with D-branes)

• Is closer to traditional model building

• The downside: it is not always embedable in string theory

Gepner Orientifolds

• Despite all the hopes put on orientifold vacua, close analogues of the SM are hard to come by

• By and large the biggest collection of orientifold vacua fitting the chiral characteristics of the (Supersymmetric) standard model have been constructed using RCFT techniques and computerized search algorithms (pioneered by B. Schellekens).

• All tadpole solutions to "Madrid hypercharge embeddings" models were found on Gepner orientifolds (about 2×10^5)

Dijkstra+Huiszoon+Schellekens

• All different profiles of hypercharge embeddings and chiral spectra were classified in the same context:around 19000 top-down configurations out of which about 1900 had at least one tadpole solution.

Anastasopoulos+Dijkstra+Kiritsis+Schellekens

Free field Orientifolds

• The downside in the Gepner arena is that further important dynamical ingredients are so far hard to calculate

♠the open+closed string superpotential is a crucial ingredient of realistic low energy physics (full moduli stabilisation and susy breaking complete the list). This is difficult to calculate.

• This motivates searching other classes of orientifold vacua, that are related to RCFTs that are easier to calculate with.

• An example from the heterotic string is that of "fermionic vacua"

Kawai+Lewellen+Tye
Antoniadis+Bachas+Kounnas

this allowed a computerized algorithmic search (albeit a non-systematic one)

Antoniadis+Leontaris+Rizos, Rizos
Faraggi+Kounnas+Rizos

Fermionic orientifolds

Kiritsis+Lennek+Schellekens

- Based on RCFT build out of Free fermions

- Construction implemented by the simple-current extension technique

- Encompasses a large subset of Free Fermion Orientifolds (But not all)

- a few TOP-DOWN solutions found but NO TADPOLE solutions

- 3 families seems to be a stringent constraint.

- There seems to be also a lot of redundancy

Gepner models out of free fields

• There are two Gepner models that are equivalent to free fields:

♠ $k = 1 \rightarrow c = 1$ a free boson at radius $R = \sqrt{\frac{3}{2}}$

Friedan+Shenker, Waterson, Kiritsis

No SM vacua were found on $\{k = 1\}^9 \sim Z_3$ torroidal orbifold

♠ $k = 2 \rightarrow c = 3/2$ $\sim$ with 12 NS primaries and 12 R primaries.
It is a $R = 2$ free boson $\otimes$ an Ising fermion. At $R = 2$, there are 5 nontrivial chiral primaries with $\Delta = \frac{1}{16}$ (2), $\Delta = \frac{1}{4}$, $\Delta = 1$ (2)

• We have scanned for SM spectra and associated tadpole solutions in the $\{k = 2\}^6$ compactification, all its simple current extensions and all associated orientifold projections and found :

several copies of 9 interesting spectra.

The most promising $\{k=2\}^6$ spectrum

Chiral number	U(3)	SU(2)	$U(1)_c$	$U(1)_d$	$SU(2)_h$	Y	Symbol
3	V	V	0	0	0	$\frac{1}{6}$	Q
-2	V	0	V	0	0	$-\frac{2}{3}$	$\overline{U}$
-2	V	0	0	V	0	$-\frac{2}{3}$	$\overline{\mathcal{U}}$
1	V	0	0	V	0	$\frac{2}{3}$	$\mathcal{U}$
-2	V	0	V*	0	0	$\frac{1}{3}$	$\overline{D}$
-1	V	0	0	V*	0	$\frac{1}{3}$	$\overline{\mathcal{D}}$
2	0	V	0	V	0	$\frac{1}{2}$	L
2	0	V	V	0	0	$\frac{1}{2}$	H
-1	0	V	V	0	0	$-\frac{1}{2}$	$\overline{\mathrm{H}}$
-3	0	0	V	V	0	-1	$\overline{E}_R$
1	0	0	V	V*	0	0	N
2-2	0	0	V	0	V	$\pm\frac{1}{2}$	X
2-2	S	0	0	0	0	$\pm\frac{1}{3}$	Z
1-1	0	0	0	S	0	± 1	P
1-1	0	0	0	0	A	0	R
1	0	0	0	0	S	0	T

$$V \to \square,\ V^* \to \overline{\square},\ A \to \begin{smallmatrix}\square\\\square\end{smallmatrix},\ S \to \square\square$$

The most promising $\{k=2\}^6$ spectrum: Part II

- Very simple and potentially interesting hidden sector

- Hypercharge of Madrid type

$$Y = \frac{1}{6}Q_a + \frac{1}{2}Q_c + \frac{1}{2}Q_d$$

- Baryon number is a global symmetry but not lepton number

- Two out of the three generations of quarks singlets are sequestered
(potentially good for generating a hierarchy of masses)

- Two out of the three generations of lepton doublets are sequestered

- There is one right-handed neutrino candidate in the "observable" stack,
but another two absolute singlets on the hidden brane

The other $\{k=2\}^6$ spectra

♠Two other models with same gauge group: In the first

- SU(3) $\quad 4\ \square\!\square \rightarrow 2\ \square\!\square \oplus 2\ \begin{array}{c}\square\\[-4pt]\square\end{array}$

- $\mathrm{U}(1)_d \quad 2\ \square\!\square \rightarrow 2\ \begin{array}{c}\square\\[-4pt]\square\end{array}$

- $\mathrm{SU}(2)_d \quad 2\ \begin{array}{c}\square\\[-4pt]\square\end{array} \rightarrow 2\ \square\!\square$

In the second:

- SU(3) $\quad 4\ \square\!\square \rightarrow 4\ \begin{array}{c}\square\\[-4pt]\square\end{array}$

- $\mathrm{SU}(2)_d \quad 2\ \begin{array}{c}\square\\[-4pt]\square\end{array} \rightarrow 2\ \square\!\square$

♠ 5 more models where the hidden gauge group is O(2)

- On all spectra the SM part is similar (charge-wise).

What next?

- This is a vacuum that is constructed out of (almost) free fields.

- With some effort, the superpotential and may be other tree-level interactions may be computable.

- Before embarking in that, we should make a rough analysis of the phenomenological viability of this setup.

- We will assume, that all couplings that are allowed by charge conservation, and D-brane selection rules are there with natural coefficients (modulo SUSY breaking)

- In particular we will assume that the Higgs vevs are in the 200 GeV region.

- Of course we must move a bit in closed string moduli space so that the non-chiral exotics get masses at the string scale (that we will take close to the Planck scale).

The low energy spectrum

Chiral number	U(3)	SU(2)	$U(1)_c$	$U(1)_d$	$SU(2)_h$	Y	Symbol
3	V	V	0	0	0	$\frac{1}{6}$	Q
2	V*	0	V*	0	0	$\frac{2}{3}$	U
1	V*	0	0	V*	0	$\frac{2}{3}$	$\mathcal{U}$
2	V*	0	V	0	0	$-\frac{1}{3}$	D
1	V*	0	0	V	0	$-\frac{1}{3}$	$\mathcal{D}$
2	0	V	0	V	0	$\frac{1}{2}$	L
2	0	V	V	0	0	$\frac{1}{2}$	H
1	0	V*	V*	0	0	$-\frac{1}{2}$	$\overline{\mathrm{H}}$
3	0	0	V*	V*	0	-1	E
1	0	0	V	V*	0	0	N
1-1	0	0	0	0	A	0	R

- The non-chiral pairs, $\mathcal{U},\overline{\mathcal{U}}$, and all other non-chiral exotic fields are expected to get masses at M_s and be integrated out

- The rest will have a superpotential of the form:

$$W_2^p = H\overline{H} + RR$$

$$W_3^p = QUH + QD\overline{H} + Q\mathcal{U}L +$$
$$+ LN\overline{H} + LEH + H\bar{H}R + RRR$$

$$W_4^p = (QU)(LN) + (QD)(LE) + (QU)(QD) + (Q\mathcal{U})(Q\mathcal{D}) + (LL)(EN) + H\bar{H}H\bar{H} +$$
$$+ (Q\mathcal{D})\bar{H}N + (Q\mathcal{D})EH + H\bar{H}RR + W_3^p\ R$$

- Leptons need to be decided but there are many couplings that violate lepton number, without imposing extra symmetries.

Superpotential from string instantons

Group	$U(1)_a$	$U(1)_c$	$U(1)_d$
SU(3)	0	0	0
SU(2)	9	1	2
Y	$-\frac{9}{2}$	$-\frac{9}{2}$	3
$SU(2)_{\text{hidden}}$	0	0	0
gravity	0	0	0

- Baryon number is only violated by SU(2) gauge instantons
- No mixed gravitational anomalies
- Two basic "string instantons" violating ($U(1)_c$,$U(1)_d$) charge by $\pm(1,-1)$ units

$$W_{+}^{np} = QUL + Q\mathcal{D}\bar{H} + LLE + L\bar{H}$$

$$W_{-}^{np} = QDL + Q\mathcal{U}H + EHH + H\bar{H}N + N \quad , \quad W_{--}^{np} = NN$$

D-terms in orientifolds

• An important contribution to the potential comes from the D-terms.

• In (exact) BCFT vacua, the FI term of unbroken U(1) symmetries is zero at tree level.

• In orbifolds it was suggested that this is still true at one loop

Poppitz

• This is true in all such BCFT vacua :

• Diagram to calculate: two point function (Mass) of charged scalars at one loop.

• Similar to the calculation of the mass of anomalous U(1) gauge bosons:

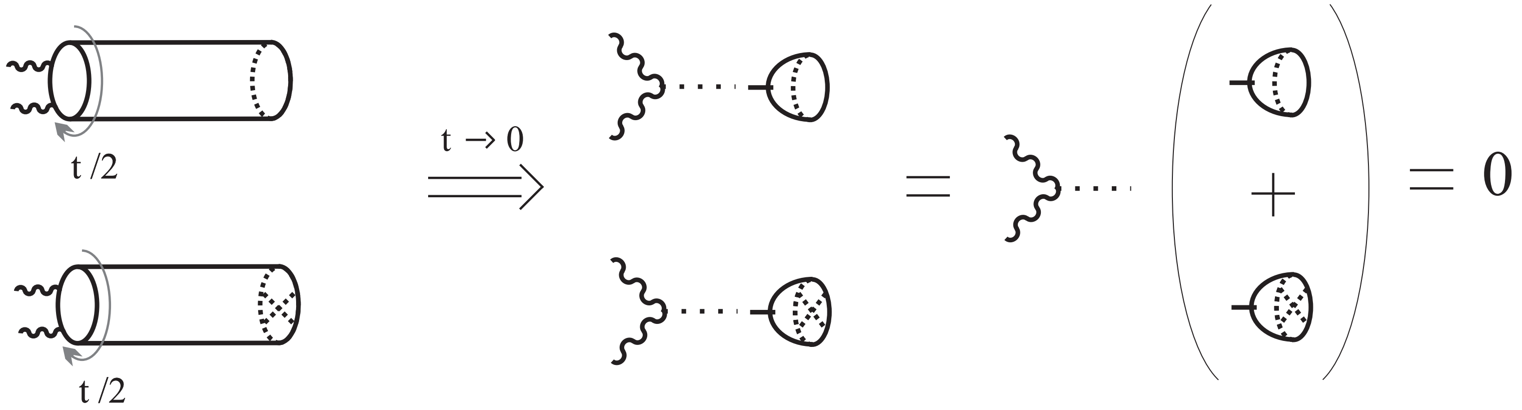
Antoniadis+Kiritsis+Rizos

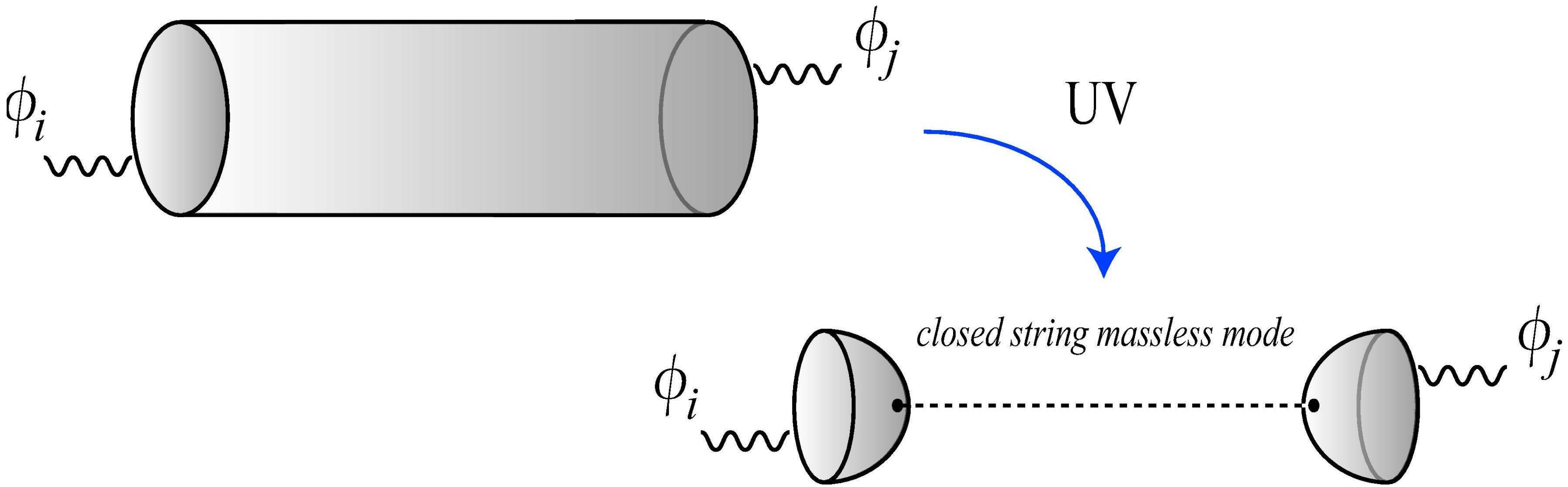
(1) kinematic factor is $\mathcal{O}(p^2)$

(2) Mass needs a $\frac{1}{p^2}$ pole

(3) This originates from the UV (open)= IR (closed) and is a contact term.

(4) Can be calculated in the strict $t \to 0$ limit.





Q.E.D.

Higgses vs Leptons

• We have 4 particles with lepton doublet quantum numbers: 2 H and 2 L. The simplest possibility is that one Higgs is a linear combination of the two $H's$ (the other is $\bar{H}$).

• There are more complex possibilities like a linear combination of both Hs and Ls getting a vev but we will not explore them here.

• Baryon number is conserved to a large accuracy (broken only by SU(2) instantons).

• There is a generic lepton violation problem here: in the absence of baryon number violation it puts strong constraints only for the cubic superpotential.

• Such constraints will be effective if there is an appropriate discrete symmetry in the theory.

• An (non-unique) example that could do the job is

$$H^1 \leftrightarrow H^2 \quad , \quad L^i \to -L^i \quad , \quad E^a \to -E^a \quad , \quad N \to -N \quad , \quad R^i \to -R^i$$

This implies that one of the Higgses is $H^1 + H^2 \to H$ while the third lepton is $H^1 - H^2 \to \tilde{L}$.

$$W^p = H\overline{H} + RR + QUH + QD\overline{H} + LN\overline{H} + LEH + \tilde{L}\bar{H}R$$

$$W^{np} = \left\{Q\mathcal{D}\bar{H} + L\bar{H}R\right\} + \left\{Q\mathcal{U}H + E\tilde{L}H + \tilde{L}\bar{H}N + NR\right\} + NN$$

• The $\mathcal{U}$ and $\mathcal{D}$ can be associated with the first generation as their masses will be suppressed by the instanton effects.

Neutrino masses

- The superpotential allows for a see-saw mechanism for neutrinos

$$W_\nu = RR + LN\overline{H} + \tilde{L}\bar{H}R + \tilde{L}\tilde{L}\bar{H}^2 + L\bar{H}R + \tilde{L}\bar{H}N + NN + NR$$

with the following mass matrix:

	L^1	L^2	$\tilde{L}$	N	R^1	R^2
L^1	0	0	0	v	v e^{-S}	v e^{-S}
L^2	0	0	0	v	v e^{-S}	v e^{-S}
$\tilde{L}$	0	0	$\frac{v^2}{M_s}$	v e^{-S}	v	v
N	v	v	v e^{-S}	M_s e^{-2S}	M_s e^{-S}	M_s e^{-S}
R^1	v e^{-S}	v e^{-S}	v	M_s e^{-S}	M_s	M_s
R^1	v e^{-S}	v e^{-S}	v	M_s e^{-S}	M_s	M_s

- Good values for neutrino masses can be obtained for appropriate choices of $M_s \sim M_{GUT}$, e^{-S}.

Outlook

• There is a class of interesting looking MSSM-like vacua made out of the free-field $k = 2$ Gepner model.

• They seem to have the ingredients to withstand a first order phenomenological assault.

• This justifies the investment of extra effort to calculate their perturbative and non-perturbative superpotential.

• The physical separation of one family gives hints on generating a hierarchy of masses using the presence of anomalous U(1) symmetries and gauge/string instanton effects in a more general context.

The quartic superpotential with Lepton discrete symmetry

$$W_4^p = (QU)(LN)+(QD)(LE)+(QU)(QD)+(Q\mathcal{U})(Q\mathcal{D})+(LL)(EN)+H\bar{H}H\bar{H}+$$

$$+\tilde{L}\tilde{L}\bar{H}\bar{H}+(Q\mathcal{D})E\tilde{L}+H\bar{H}RR+(QU\tilde{L}+Q\mathcal{U}L+LE\tilde{L}+H\bar{H}R+RRR)R$$

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