Non-supersymmetric heterotic model building

Stefan Groot Nibbelink

Arnold Sommerfeld Center, Ludwig-Maximilians-University, Munich

based on

arXiv:1407.6362

together with:

Michael Blaszczyk, Orestis Loukas,
Saul Ramos-Sánchez

Overview of this talk

1. Motivation
2. The non-supersymmetric heterotic string
3. Orbifold compactifications
4. Smooth Calabi-Yau compactifications
5. Orbifold model searches
6. Conclusion

MSSM from String Theory

Conventionally in string model building one is looking for string models which get close to the MSSM, i.e.:

- a 4D $\mathcal{N} = 1$ supersymmetric gauge theory
- gauge group containing $SU(3)_C \times SU(2)_L \times U(1)_Y$
- three net chiral generations of quarks and leptons
- at least one Higgs doublet pair

Calabi-Yaus with vector bundles

The basic requirement is that one obtains an effective 4D field theory with $\mathcal{N} = 1$ SUSY from the heterotic string:

Candelas,Horowitz,Strominger,Witten'85

$$\mathcal{M}^{1,9} \to \mathcal{M}^{1,3} \times \mathcal{M}^6$$

- a six dimensional Calabi-Yau manifold $\mathcal{M}^6$ with vanishing first Chern class
- a gauge background satisfying the Hermitean Yang–Mills equations characterized by a vector bundle

Toroidal orbifold geometries

The idea of orbifolds is that they are very simple geometries yet shared the main property of Calabi–Yau manifolds namely that only 4D $\mathcal{N} = 1$ SUSY survives.

Dixon,Harvey,Vafa,Witten'85, Ibanez,Mas,Nilles,Quevedo'87

Toroidal orbifolds are defined as

$$T^6/G$$

with some six dimensional torus T^6 and a finite group G, like $\mathbb{Z}_N$

Model building results

MSSM–like models on Calabi–Yaus:

- Stable $SU(5)$ vector bundles on Schoen manifold
  Donagi,Ovrut,Pantev,Waldram'00, Bouchard,Donagi'05, Braun,He,Ovrut,Pantev'05
- Line bundles on complete intersection Calabi–Yaus
  Anderson,Gray,Lukas,Palti'11

MSSM–like models on Orbifolds:

- $T^6/\mathbb{Z}_{6\text{-II}}$ Buchmuller,Hamaguchi,Lebedev,Ratz'05,
  Lebedev,Nilles,Raby,Ramos-Sanchez,Ratz,Vaudrevange,Wingerter'06
- $T^6/\mathbb{Z}_{12-I}$ Kim,Kim,Kyae'07
- $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ Blaszczyk,SGN,Ratz,Ruehle,Trapletti,Vaudrevange'09
- $T^6/\mathbb{Z}_4 \times \mathbb{Z}_2$ Mayorga-Pena,Nilles,Oehlmann'12
- $T^6/\mathbb{Z}_{8\text{-I,II}}$ SGN,Loukas'13

Comprehensive overview Vaudrevange,Nilles'14

But where is supersymmetry?

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt$[fb^{-1}]		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde q,\tilde g$	1.7 TeV	m($\tilde q$)=m($\tilde g$)	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde g$	1.2 TeV	any m($\tilde q$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde g$	1.1 TeV	any m($\tilde q$)	1308.1841
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$	0	2-6 jets	Yes	20.3	$\tilde q$	850 GeV	m($\tilde\chi^0_1$)=0 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	1405.7875
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi^0_1$	0	2-6 jets	Yes	20.3	$\tilde g$	1.33 TeV	m($\tilde\chi^0_1$)=0 GeV	1405.7875
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^\pm_1\to qqW^\pm\tilde\chi^0_1$	1 e,μ	3-6 jets	Yes	20.3	$\tilde g$	1.18 TeV	m($\tilde\chi^0_1$)<200 GeV, m($\tilde\chi^\pm$)=0.5(m($\tilde\chi^0_1$)+m($\tilde g$))	ATLAS-CONF-2013-062
	$\tilde g\tilde g$, $\tilde g\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde\chi^0_1$	2 e,μ	0-3 jets	-	20.3	$\tilde g$	1.12 TeV	m($\tilde\chi^0_1$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde\ell$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde g$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde\ell$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde g$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde g$	1.28 TeV	m($\tilde\chi^0_1$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde g$	619 GeV	m($\tilde\chi^0_1$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde g$	900 GeV	m($\tilde\chi^0_1$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde g$	690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde G$)>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde g$ med.	$\tilde g\to b\bar b\tilde\chi^0_1$	0	3 b	Yes	20.1	$\tilde g$	1.25 TeV	m($\tilde\chi^0_1$)<400 GeV	1407.0600
	$\tilde g\to t\bar t\tilde\chi^0_1$	0	7-10 jets	Yes	20.3	$\tilde g$	1.1 TeV	m($\tilde\chi^0_1$) <350 GeV	1308.1841
	$\tilde g\to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$	1.34 TeV	m($\tilde\chi^0_1$)<400 GeV	1407.0600
	$\tilde g\to b\bar t\tilde\chi^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$	1.3 TeV	m($\tilde\chi^0_1$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi^0_1$	0	2 b	Yes	20.1	$\tilde b_1$	100-620 GeV	m($\tilde\chi^0_1$)<90 GeV	1308.2631
	$\tilde b_1\tilde b_1$, $\tilde b_1\to t\tilde\chi^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde b_1$	275-440 GeV	m($\tilde\chi^\pm_1$)=2 m($\tilde\chi^0_1$)	1404.2500
	$\tilde t_1\tilde t_1$(light), $\tilde t_1\to b\tilde\chi^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde t_1$	110-167 GeV	m($\tilde\chi^0_1$)=55 GeV	1208.4305, 1209.2102
	$\tilde t_1\tilde t_1$(light), $\tilde t_1\to Wb\tilde\chi^0_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde t_1$	130-210 GeV	m($\tilde\chi^0_1$) =m($\tilde t_1$)-m(W)-50 GeV, m($\tilde t_1$)<<m($\tilde\chi^\pm_1$)	1403.4853
	$\tilde t_1\tilde t_1$(medium), $\tilde t_1\to t\tilde\chi^0_1$	2 e,μ	2 jets	Yes	20.3	$\tilde t_1$	215-530 GeV	m($\tilde\chi^0_1$)=1 GeV	1403.4853
	$\tilde t_1\tilde t_1$(medium), $\tilde t_1\to b\tilde\chi^\pm_1$	0	2 b	Yes	20.1	$\tilde t_1$	150-580 GeV	m($\tilde\chi^0_1$)<200 GeV, m($\tilde\chi^\pm_1$)-m($\tilde\chi^0_1$)=5 GeV	1308.2631
	$\tilde t_1\tilde t_1$(heavy), $\tilde t_1\to t\tilde\chi^0_1$	1 e,μ	1 b	Yes	20	$\tilde t_1$	210-640 GeV	m($\tilde\chi^0_1$)=0 GeV	1407.0583
	$\tilde t_1\tilde t_1$(heavy), $\tilde t_1\to t\tilde\chi^0_1$	0	2 b	Yes	20.1	$\tilde t_1$	260-640 GeV	m($\tilde\chi^0_1$)=0 GeV	1406.1122
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde t_1$	90-240 GeV	m($\tilde t_1$)-m($\tilde\chi^0_1$)<85 GeV	1407.0608
	$\tilde t_1\tilde t_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde t_1$	150-580 GeV	m($\tilde\chi^0_1$)>150 GeV	1403.5222
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde t_2$	290-600 GeV	m($\tilde\chi^0_1$)<200 GeV	1403.5222
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi^0_1$	2 e,μ	0	Yes	20.3	$\tilde\ell$	90-325 GeV	m($\tilde\chi^0_1$)=0 GeV	1403.5294
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to\tilde\ell\nu(\ell\tilde\nu)$	2 e,μ	0	Yes	20.3	$\tilde\chi^\pm_1$	140-465 GeV	m($\tilde\chi^0_1$)=0 GeV, m($\tilde\ell,\tilde\nu$)=0.5(m($\tilde\chi^\pm_1$)+m($\tilde\chi^0_1$))	1403.5294
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to\tilde\tau\nu(\tau\tilde\nu)$	2 τ	-	Yes	20.3	$\tilde\chi^\pm_1$	100-350 GeV	m($\tilde\chi^0_1$)=0 GeV, m($\tilde\tau,\tilde\nu$)=0.5(m($\tilde\chi^\pm_1$)+m($\tilde\chi^0_1$))	1407.0350
	$\tilde\chi^\pm_1\tilde\chi^0_2\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	20.3	$\tilde\chi^\pm_1,\tilde\chi^0_2$	700 GeV	m($\tilde\chi^\pm_1$)=m($\tilde\chi^0_2$), m($\tilde\chi^0_1$)=0, m($\tilde\ell,\tilde\nu$)=0.5(m($\tilde\chi^\pm_1$)+m($\tilde\chi^0_1$))	1402.7029
	$\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1 Z\tilde\chi^0_1$	2-3 e,μ	0	Yes	20.3	$\tilde\chi^\pm_1,\tilde\chi^0_2$	420 GeV	m($\tilde\chi^\pm_1$)=m($\tilde\chi^0_2$), m($\tilde\chi^0_1$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1 h\tilde\chi^0_1$	1 e,μ	2 b	Yes	20.3	$\tilde\chi^\pm_1,\tilde\chi^0_2$	285 GeV	m($\tilde\chi^\pm_1$)=m($\tilde\chi^0_2$), m($\tilde\chi^0_1$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde\chi^0_2\tilde\chi^0_3$, $\tilde\chi^0_{2,3}\to\tilde\ell_R\ell$	4 e,μ	0	Yes	20.3	$\tilde\chi^0_{2,3}$	620 GeV	m($\tilde\chi^0_2$)=m($\tilde\chi^0_3$), m($\tilde\chi^0_1$)=0, m($\tilde\ell,\tilde\nu$)=0.5(m($\tilde\chi^0_2$)+m($\tilde\chi^0_1$))	1405.5086
Long-lived particles	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde\chi^\pm_1$	270 GeV	m($\tilde\chi^\pm_1$)-m($\tilde\chi^0_1$)=160 MeV, τ($\tilde\chi^\pm_1$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde g$	832 GeV	m($\tilde\chi^0_1$)=100 GeV, 10 μs<τ($\tilde g$)<1000 s	1310.6584
	GMSB, stable $\tilde\tau$, $\tilde\chi^0_1\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde\chi^0_1$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde\chi^0_1\to\gamma\tilde G$, long-lived $\tilde\chi^0_1$	2 γ	-	Yes	4.7	$\tilde\chi^0_1$	230 GeV	0.4<τ($\tilde\chi^0_1$)<2 ns	1304.6310
	$\tilde q\tilde q$, $\tilde\chi^0_1\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde q$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde\chi^0_1$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde\nu_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde\nu_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde q,\tilde g$	1.35 TeV	m($\tilde q$)=m($\tilde g$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to W\tilde\chi^0_1$, $\tilde\chi^0_1\to ee\tilde\nu_\mu, e\mu\tilde\nu_e$	4 e,μ	-	Yes	20.3	$\tilde\chi^\pm_1$	750 GeV	m($\tilde\chi^0_1$)>0.2×m($\tilde\chi^\pm_1$), $\lambda_{121}\neq0$	1405.5086
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to W\tilde\chi^0_1$, $\tilde\chi^0_1\to\tau\tau\tilde\nu_e, e\tau\tilde\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde\chi^\pm_1$	450 GeV	m($\tilde\chi^0_1$)>0.2×m($\tilde\chi^\pm_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde g\to qqq$	0	6-7 jets	-	20.3	$\tilde g$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde g\to\tilde t_1 t$, $\tilde t_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde g$	850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar q$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar t$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} 1 **Mass scale [TeV]**

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

Maybe we should look for non-supersymmetric string models...

Previous attempts:

- Free fermionic construction with non-supersymmetric boundary conditions

  Dienes'94,'06, Faraggi,Tsulaia'07

- Non-supersymmetric orbifolds of heterotic theories

  Chamseddine,Derendinger,Quiros'88, Taylor'88, Toon'90, Sasada'95, Font,Hernandez'02

- Non-supersymmetric orientifold type II theories

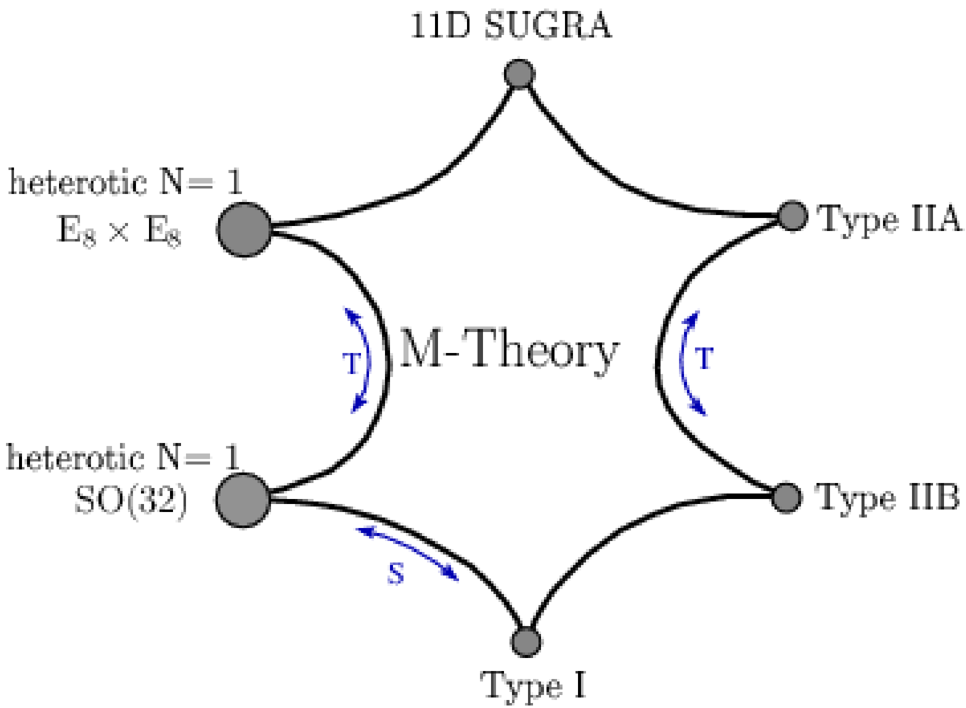
  Sagnotti'95, Angelantonj'98 Blumenhagen,Font,Luest'99, Aldazabal,Ibanez,Quevedo'99

- Non-supersymmetric RCFTs

  Gato-Rivera,Schellekens'07

Well-known 10D string theories

The M-theory cartoon displays the modular invariant, anomaly- and tachyon-free 10D string theories:



However, it disregards one interesting heterotic string theory...

The non-supersymmetric heterotic string

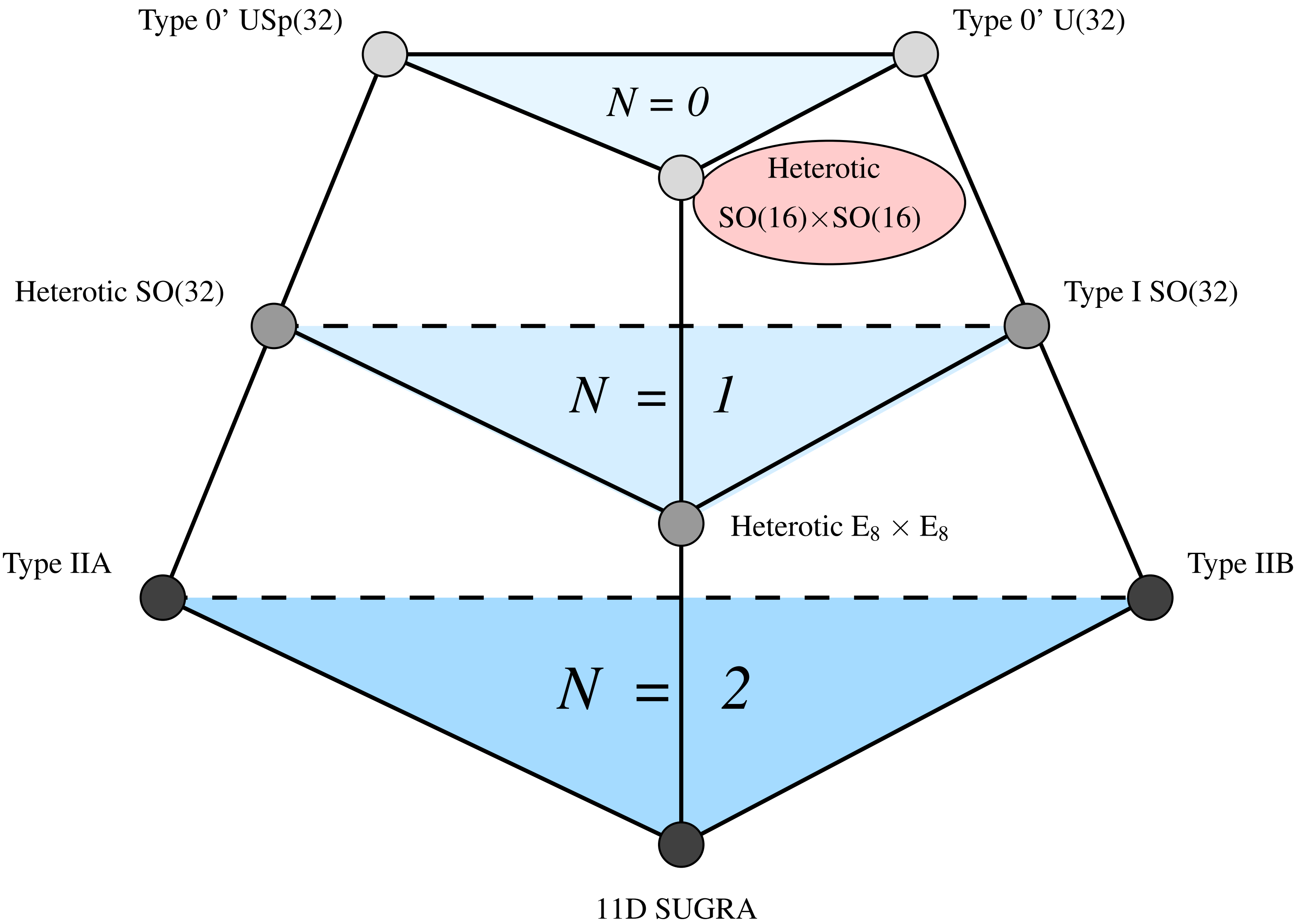
The low-energy spectrum of the N=0 heterotic string reads:

Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

	Fields	10D space-time interpretation
Bosons	G_{MN}, B_{MN}, ϕ	Graviton, Kalb-Ramond 2-form, Dilaton
	A_M	SO(16)$\times$SO(16) Gauge fields
Fermions	Ψ_+	Spinors in the $(\mathbf{128}, \mathbf{1}) + (\mathbf{1}, \mathbf{128})$
	Ψ_-	Cospinors in the $(\mathbf{16}, \mathbf{16})$

This theory is also modular invariant, anomaly- and tachyon-free but obviously not supersymmetric

10D tachyon-free (non)SUSY string theories



Construction of the N=0 heterotic string I

Introduce discrete torsion phases in the $E_8 \times E_8$ heterotic string:

I.e. replace the partition function:

$$\mathbf{Z}_{E_8^2} = \sum_{\text{spin}} \quad \mathbf{Z}_8^x(\tau,\bar{\tau}) \cdot \widehat{\mathbf{Z}}_4 \left[{}^{s}_{s'}\right](\tau) \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{}^{t}_{t'}\right](\tau)} \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{}^{u}_{u'}\right](\tau)}$$

(where s, t, u label the spin structures) by:

$$\mathbf{Z}_{N=0} = \sum_{\text{spin}} T \cdot \mathbf{Z}_8^x(\tau,\bar{\tau}) \cdot \widehat{\mathbf{Z}}_4 \left[{}^{s}_{s'}\right](\tau) \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{}^{t}_{t'}\right](\tau)} \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{}^{u}_{u'}\right](\tau)}$$

with torsion phase

$$T = (-)^{st'-s't} * \ldots \quad * \quad (-)^{s's+s'+s} * \ldots$$

Construction of the N=0 heterotic string II

Perform the $\mathbb{Z}_2$ orbifold of the supersymmetric $E_8 \times E_8$ in the lattice formulation:

$$\mathbf{Z}_{E_8^2} = \mathbf{Z}_8^x(\tau, \overline{\tau}) \cdot \mathbf{\Gamma}_4(\tau) \cdot \overline{\mathbf{\Gamma}_{16}(\tau)}$$

where $\mathbf{\Gamma}_4$ and $\mathbf{\Gamma}_{16}$ are appropriate lattice sums

The $\mathbb{Z}_2$ orbifold is defined by twist v_0 and gauge shift V_0:

$$v_0 = (0, 1^3)\ , \qquad V_0 = (1, 0^7)(\text{-}1, 0^7)$$

which breaks target space supersymmetry completely

Appendix I: Some lattices

	Weight lattice	Lattice vectors
$\mathbf{R}_D$	Root	$n \in \mathbb{Z}^D, \sum n_i \in 2\mathbb{Z}$
$\mathbf{V}_D$	Vector	$n \in \mathbb{Z}^D, \sum n_i \in 2\mathbb{Z}+1$
$\mathbf{S}_D$	Spinor	$n \in \mathbb{Z}^D + \frac{1}{2}e_D, \sum n_i \in 2\mathbb{Z}$
$\mathbf{C}_D$	Cospinor	$n \in \mathbb{Z}^D + \frac{1}{2}e_D, \sum n_i \in 2\mathbb{Z}+1$
$\mathbf{\Gamma}_4$	Space-time	$\mathbf{V}_4 \oplus \mathbf{S}_4$
$\mathbf{E}_8$	E_8 Root	$\mathbf{R}_8 \oplus \mathbf{S}_8$
$\mathbf{\Gamma}_{16}$	$\mathrm{E}_8 \times \mathrm{E}_8$ Root	$\mathbf{E}_8 \oplus \mathbf{E}_8$

This orbifolding replaces the red lattices by green lattices:

	Sector (s,t,u)	Lattices in the theory: N=1, $E_8 \times E_8$	N=0, $SO(16) \times SO(16)$
Bosons	(1,1,1)	$\mathbf{V}_4 \otimes \mathbf{R}_8 \otimes \mathbf{R}_8$	$\mathbf{V}_4 \otimes \mathbf{R}_8 \otimes \mathbf{R}_8$
	(1,0,0)	$\mathbf{V}_4 \otimes \mathbf{S}_8 \otimes \mathbf{S}_8$	$\mathbf{V}_4 \otimes \mathbf{S}_8 \otimes \mathbf{S}_8$
	(1,0,1)	$\mathbf{V}_4 \otimes \mathbf{S}_8 \otimes \mathbf{R}_8$	$\mathbf{R}_4 \otimes \mathbf{C}_8 \otimes \mathbf{V}_8$
	(1,1,0)	$\mathbf{V}_4 \otimes \mathbf{R}_8 \otimes \mathbf{S}_8$	$\mathbf{R}_4 \otimes \mathbf{V}_8 \otimes \mathbf{C}_8$
Fermions	(0,0,1)	$\mathbf{S}_4 \otimes \mathbf{S}_8 \otimes \mathbf{R}_8$	$\mathbf{S}_4 \otimes \mathbf{S}_8 \otimes \mathbf{R}_8$
	(0,1,0)	$\mathbf{S}_4 \otimes \mathbf{R}_8 \otimes \mathbf{S}_8$	$\mathbf{S}_4 \otimes \mathbf{R}_8 \otimes \mathbf{S}_8$
	(0,1,1)	$\mathbf{S}_4 \otimes \mathbf{R}_8 \otimes \mathbf{R}_8$	$\mathbf{C}_4 \otimes \mathbf{V}_8 \otimes \mathbf{V}_8$
	(0,0,0)	$\mathbf{S}_4 \otimes \mathbf{S}_8 \otimes \mathbf{S}_8$	$\mathbf{C}_4 \otimes \mathbf{C}_8 \otimes \mathbf{C}_8$

Orbifolding the N=0 theory

A $\mathbb{Z}_N$ orbifold is defined by the worldsheet boundary conditions:

$$X^i(\sigma+1) = e^{2\pi i k v_i}\, X^i(\sigma)\,, \qquad \psi^i(\sigma+1) = e^{2\pi i(\frac{s}{2}+kv_i)}\, \psi^i(\sigma)\,,$$

$$\lambda_1^I(\sigma+1) = e^{2\pi i(\frac{t}{2}+kV_{1I})}\, \lambda_1^I(\sigma)\,, \qquad \lambda_2^I(\sigma+1) = e^{2\pi i(\frac{u}{2}+kV_{2I})}\, \lambda_2^I(\sigma)$$

encoded in a twist v and gauge shift $V=(V_1;V_2)$with:

$$N\,v_i \equiv 0\,, \qquad N\,V_{1,2} \in \mathbf{E}_8$$

Conditions from modular invariance

We focus $\mathbb{Z}_N$ orbifold twists that would preserve at least 4D, N=1 supersymmetry if we apply to the $E_8 \times E_8$ theory:

$$v = (v_1, v_2, -v_1 - v_2)$$

We require that we have modular invariant partition function for the orbifolded N=0 theory in the lattice formulation:

$$\frac{N}{2}(V^2 - v^2) \equiv V_0 \cdot V \equiv 0$$

The spectra can be computed as usual from the partition function...

Some $\mathbb{Z}_3$ orbifold models

Orbifold shift V / Gauge group G	Massless spectrum on orbifold: chiral fermions / complex bosons
$\frac{1}{3}(0, 1^2, \text{-}2, 0^4)(0^8)$	$3(\mathbf{3},\mathbf{1};\mathbf{16}) + 3(\overline{\mathbf{3}},\overline{\mathbf{16}};\mathbf{1}) + 27(\mathbf{1},\overline{\mathbf{16}};\mathbf{1}) + (\mathbf{1},\overline{\mathbf{16}};\mathbf{1})$ $+(\mathbf{1},\mathbf{16};\mathbf{1}) + (\mathbf{1};\mathbf{128}) + (\mathbf{1},\mathbf{10};\mathbf{16}) + 27(\mathbf{1};\mathbf{16})$
U(3)×SO(10)×SO(16)'	$81(\overline{\mathbf{3}},\mathbf{1};\mathbf{1}) + 3(\mathbf{3},\mathbf{1};\mathbf{1}) + 3(\mathbf{3},\mathbf{10};\mathbf{1}) + 27(\mathbf{1};\mathbf{1}) + 27(\mathbf{1},\mathbf{10};\mathbf{1})$
$\frac{1}{3}(1^6, 0^2)(1^6, 0^2)$	$3(\overline{\mathbf{6}},\mathbf{2}_-;\mathbf{1}) + 3(\mathbf{1};\overline{\mathbf{6}},\mathbf{2}_-) + 3(\mathbf{15},\mathbf{2}_+;\mathbf{1}) + 3(\mathbf{1};\mathbf{15},\mathbf{2}_+)$ $+3(\overline{\mathbf{6}},\mathbf{1};\overline{\mathbf{6}},\mathbf{1}) + 3(\mathbf{1},\mathbf{4};\mathbf{6},\mathbf{1}) + 3(\mathbf{6},\mathbf{1};\mathbf{1},\mathbf{4}) + (\mathbf{20},\mathbf{2}_-;\mathbf{1})$ $+(\mathbf{1};\mathbf{20},\mathbf{2}_-) + (\mathbf{1},\mathbf{4};\mathbf{1},\mathbf{4}) + 29(\mathbf{1};\mathbf{1},\mathbf{2}_+) + 29(\mathbf{1},\mathbf{2}_+;\mathbf{1})$ $+(\mathbf{6},\mathbf{1};\overline{\mathbf{6}},\mathbf{1}) + (\overline{\mathbf{6}},\mathbf{1};\mathbf{6},\mathbf{1}) + 27(\mathbf{1},\mathbf{2}_-;\mathbf{1},\mathbf{2}_-)$
U(6)×SO(4)×U(6)'×SO(4)'	$3(\overline{\mathbf{15}},\mathbf{1};\mathbf{1}) + 3(\mathbf{1};\overline{\mathbf{15}},\mathbf{1}) + 3(\mathbf{6},\mathbf{4};\mathbf{1}) + 3(\mathbf{1};\mathbf{6},\mathbf{4})$ $+27(\mathbf{1},\mathbf{2}_+;\mathbf{1},\mathbf{2}_+) + 27(\mathbf{1};\mathbf{1})$
$\frac{1}{3}(1^8)(1^4, 0^4)$	$3(\mathbf{8};\mathbf{1},\mathbf{8}_s) + 3(\mathbf{1};\mathbf{1},\mathbf{8}_c) + 3(\mathbf{1};\mathbf{4},\mathbf{8}_v) + 3(\overline{\mathbf{28}};\mathbf{1}) + 3(\overline{\mathbf{8}};\overline{\mathbf{4}},\mathbf{1})$ $+(\mathbf{70};\mathbf{1}) + (\mathbf{1};\mathbf{6},\mathbf{8}_c) + 27(\mathbf{1};\mathbf{1},\mathbf{6}) + 81(\mathbf{1};\mathbf{1}) + 3(\mathbf{1};\mathbf{1})$ $+(\mathbf{8};\overline{\mathbf{4}},\mathbf{1}) + (\overline{\mathbf{8}};\mathbf{4},\mathbf{1})$
U(8)×U(4)'×SO(8)'	$3(\overline{\mathbf{28}};\mathbf{1}) + 3(\mathbf{1};\mathbf{6},\mathbf{1}) + 3(\mathbf{1};\mathbf{4},\mathbf{8}_c) + 27(\mathbf{1};\mathbf{1},\mathbf{8}_s) + 27(\mathbf{1};\mathbf{1})$

All models are free of non-Abelian anomalies and possess at most one universal anomalous U(1)

Twisted tachyons

In some twisted sectors tachyons may arise for certain orbifolds:

Orbifold	Twist	Tachyons	Orbifold	Twists	Tachyons
$T^6/\mathbb{Z}_3$	$\frac{1}{3}(1,1,-2)$	forbidden	$T^6/\mathbb{Z}_2\times\mathbb{Z}_2$	$\frac{1}{2}(1,-1,0)\,;\ \frac{1}{2}(0,1,-1)$	forbidden
$T^6/\mathbb{Z}_4$	$\frac{1}{4}(1,1,-2)$	forbidden	$T^6/\mathbb{Z}_2\times\mathbb{Z}_4$	$\frac{1}{2}(1,-1,0)\,;\ \frac{1}{4}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{6\text{-I}}$	$\frac{1}{6}(1,1,-2)$	possible	$T^6/\mathbb{Z}_2\times\mathbb{Z}_{6\text{-I}}$	$\frac{1}{2}(1,-1,0)\,;\ \frac{1}{6}(1,1,-2)$	possible
$T^6/\mathbb{Z}_{6\text{-II}}$	$\frac{1}{6}(1,2,-3)$	possible	$T^6/\mathbb{Z}_2\times\mathbb{Z}_{6\text{-II}}$	$\frac{1}{2}(1,-1,0)\,;\ \frac{1}{6}(0,1,-1)$	possible
$T^6/\mathbb{Z}_7$	$\frac{1}{7}(1,2,-3)$	possible	$T^6/\mathbb{Z}_3\times\mathbb{Z}_3$	$\frac{1}{3}(1,-1,0)\,;\ \frac{1}{3}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{8\text{-I}}$	$\frac{1}{8}(1,2,-3)$	possible	$T^6/\mathbb{Z}_3\times\mathbb{Z}_6$	$\frac{1}{3}(1,-1,0)\,;\ \frac{1}{6}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{8\text{-II}}$	$\frac{1}{8}(1,3,-4)$	possible	$T^6/\mathbb{Z}_4\times\mathbb{Z}_4$	$\frac{1}{4}(1,-1,0)\,;\ \frac{1}{4}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{12\text{-I}}$	$\frac{1}{12}(1,4,-5)$	possible	$T^6/\mathbb{Z}_6\times\mathbb{Z}_6$	$\frac{1}{6}(1,-1,0)\,;\ \frac{1}{6}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{12\text{-II}}$	$\frac{1}{12}(1,5,-6)$	possible			

The red entries indicate that for these orbifolds twisted oscillator states may even arise

When tachyons are possible this does not mean that all such orbifold models actually have tachyons

Smooth Calabi-Yau compactifications

In principle we could compactify the N=0 theory on any smooth 6D manifold $\mathcal{M}^6$.

But then we do not have any practical computation control to compute spectra!

Therefore we consider smooth Calabi-Yau compactifications with complex vector bundles of the heterotic N=0 theory

Subject to the Bianchi identities

$$\int_{\mathcal{C}^4} \left\{ \text{tr}\, \mathcal{R}^2 - \text{tr}\, \mathcal{F}^2 \right\} = 0 \,,$$

for any closed four-cycle $\mathcal{C}^4 \subset \mathcal{M}^6$

Computation of the fermionic spectrum

For the determination of fermionic spectra we can rely on conventional methods

- (representation dependent) index theorems: ind($i\not{D}$)
- cohomology theory

In particular for line bundle backgrounds we may employ the multiplicity operator

$$\mathcal{N} = \frac{1}{6}\,\mathcal{F}_2^3 - \frac{1}{24}\,\mathcal{F}_2\,\mathrm{tr}\,\mathcal{R}_2^2$$

evaluated on all fermionic states

Computation of the bosonic spectrum

On a generic six-manifold I don't know how to determine the spectrum or even the number of zero modes of the Laplace operator Δ.

But for a smooth Calabi-Yau manifold $\mathcal{M}^6$ with a vector bundle we can use that the Laplace operator Δ for complex scalars is related to the Dirac operator $i\not{D}$ of the would be supersymmetric fermionic partners.

Hence, we can also (representation dependent) indices and cohomology theory to determine the spectra of complex scalars.

Further consequences of using a would-be supersymmetry preserving background

- To leading order there are no tachyon on smooth Calabi-Yau backgrounds in the large volume approximation
- To leading order the scalar potential V is determined by F- and D-terms:

$$V = \sum_a \left| \frac{\partial \mathcal{W}}{\partial Z^a} \right|^2 + \frac{1}{2} D^2$$

where $\mathcal{W}$ is the hypothetical superpotential of the would-be chiral superfields Z^a whose lowest components are the (massless) complex scalars.

Standard embedding compactifications

In the standard embedding we have the gauge embedding:

$$\mathrm{SO}(16) \times \mathrm{SO}(16)' \longrightarrow \mathrm{SO}(10) \times \mathrm{U}(1) \times \mathrm{SO}(16)'$$

Hence the standard embedding already gives an SO(10) GUT!

Multiplicity	Complex bosons	Chiral fermions
1	–	$(\mathbf{16};\mathbf{1})_3 + (\overline{\mathbf{16}};\mathbf{1})_{-3}$ $+(\mathbf{1};\mathbf{128})_0 + (\mathbf{10};\mathbf{16})_0$
$h^{1,1}$	$(\mathbf{10};\mathbf{1})_2 + (\mathbf{1};\mathbf{1})_{-4}$	$(\mathbf{16};\mathbf{1})_{-1} + (\mathbf{1};\mathbf{16})_{-2}$
$h^{1,2}$	$(\mathbf{10};\mathbf{1})_{-2} + (\mathbf{1};\mathbf{1})_4$	$(\overline{\mathbf{16}};\mathbf{1})_1 + (\mathbf{1};\mathbf{16})_2$
$h^1(\mathrm{End}(V))$	$(\mathbf{1};\mathbf{1})_0$	–

The net number of **16** of SO(10) is determined by: $h^{1,1} - h^{2,1}$

Resolutions of $\mathbb{Z}_3$ orbifolds

Line bundle vector W Gauge group G	Massless spectrum in blow-up: chiral fermions / complex bosons
$\frac{1}{3}(0,2^3,0^4)(0^8)$ U(3)×SO(10)×SO(16)'	$3(\mathbf{3},\mathbf{1};\mathbf{16})_2+3(\overline{\mathbf{3}},\overline{\mathbf{16}};\mathbf{1})_1+27(\mathbf{1},\overline{\mathbf{16}};\mathbf{1})_{-3}$ $78(\overline{\mathbf{3}},\mathbf{1};\mathbf{1})_{-4}+3(\mathbf{3},\mathbf{10};\mathbf{1})_{-2}$
$\frac{1}{3}(1^6,0^2)(1^6,0^2)$ U(6)×SO(4)×U(6)'×SO(8)'	$3(\overline{\mathbf{6}},\mathbf{2};\mathbf{1})_{-2}+3(\mathbf{1};\overline{\mathbf{6}},\mathbf{2})_{-2}+3(\mathbf{15},\mathbf{2};\mathbf{1})_1+3(\mathbf{1};\mathbf{15},\mathbf{2})_1$ $+3(\overline{\mathbf{6}},\mathbf{1};\overline{\mathbf{6}},\mathbf{1})_{-2}+3(\mathbf{6},\mathbf{1};\mathbf{1},\mathbf{4})_1+3(\mathbf{1},\mathbf{4};\mathbf{6},\mathbf{1})_1$ $+27(\mathbf{1},\mathbf{2};\mathbf{1})_{-3}+27(\mathbf{1};\mathbf{1},\mathbf{2})_{-3}$ $3(\overline{\mathbf{15}},\mathbf{1};\mathbf{1})_{-2}+3(\mathbf{1};\overline{\mathbf{15}},\mathbf{1})_{-2}+3(\mathbf{6},\mathbf{4};\mathbf{1})_1+3(\mathbf{1};\mathbf{6},\mathbf{4})_1$
$\frac{1}{3}(1^8)(1^4,0^4)$ U(8)×U(4)'×SO(4)	$3(\mathbf{8};\mathbf{1},\mathbf{8}_v)_1+3(\mathbf{1};\mathbf{1},\mathbf{8}_s)_{-2}+3(\mathbf{1};\mathbf{4},\mathbf{8}_c)_1+3(\overline{\mathbf{28}};\mathbf{1})_{-2}$ $+3(\overline{\mathbf{8}};\overline{\mathbf{4}},\mathbf{1})_{-2}+78(\mathbf{1};\mathbf{1})_{-4}$ $3(\overline{\mathbf{28}};\mathbf{1})_{-2}+3(\mathbf{1};\mathbf{6},\mathbf{1})_{-2}+3(\mathbf{1};\mathbf{4},\mathbf{8}_v)_1$

These spectra :

- are free of non-Abelian anomalies
- match orbifold spectra up to decoupling of vector-like states

Standard Model-like theories

Orbifold twist	#(geom)	Inequivalent scanned models	Tachyon-free percentage	SM-like tachyon-free models total	one-Higgs	two-Higgs
$\mathbb{Z}_3$	(1)	74,958	100 %	128	0	0
$\mathbb{Z}_4$	(3)	1,100,336	100 %	12	0	0
$\mathbb{Z}_{6\text{-I}}$	(2)	148,950	55 %	59	18	0
$\mathbb{Z}_{6\text{-II}}$	(4)	15,036,790	57 %	109	0	1
$\mathbb{Z}_{8\text{-I}}$	(3)	2,751,085	51 %	24	0	0
$\mathbb{Z}_{8\text{-II}}$	(2)	4,397,555	71 %	187	1	1
$\mathbb{Z}_2 \times \mathbb{Z}_2$	(12)	9,546,081	100 %	1,562	0	5
$\mathbb{Z}_2 \times \mathbb{Z}_4$	(10)	17,054,154	67 %	7,958	0	89
$\mathbb{Z}_3 \times \mathbb{Z}_3$	(5)	11,411,739	52 %	284	0	1
$\mathbb{Z}_4 \times \mathbb{Z}_4$	(5)	15,361,570	64 %	2,460	0	6

Obtained implementing the SUSY breaking $\mathbb{Z}_2$ orbifolding of the lattice formulation in the "Orbifolder package"

Nilles,Ramos-Sanchez,Vaudrevange,Wingerter'12

Appendix II: Some definitions

Two orbifold models on the same orbifold geometry are equivalent when they have:

- identical massless bosonic and fermionic and possibly tachyonic spectra up to charges under Abelian factors

Standard Model-like:

- the gauge group contains the SM gauge group with the SU(5) normalization of the non-anomalous hypercharge Y
- a net number of three generations of chiral fermions
- at least one Higgs scalar field
- vector-like exotic fermions w.r.t. the SM gauge group

A Standard Model-like theory with three generations and a single Higgs

Sector	Massless spectrum: chiral fermions / complex bosons
Observable	$3(\mathbf{3},\mathbf{2})_{1/6}+3(\overline{\mathbf{3}},\mathbf{1})_{-2/3}+6(\overline{\mathbf{3}},\mathbf{1})_{1/3}+3(\mathbf{3},\mathbf{1})_{-1/3}+3(\mathbf{1},\mathbf{1})_{1}+5(\mathbf{1},\mathbf{2})_{-1/2}$ $+2(\mathbf{1},\mathbf{2})_{1/2}+20(\mathbf{1},\mathbf{1})_{1/2}+20(\mathbf{1},\mathbf{1})_{-1/2}+6(\mathbf{3},\mathbf{1})_{1/6}+6(\overline{\mathbf{3}},\mathbf{1})_{-1/6}+2(\mathbf{1},\mathbf{2})_{0}$
Obs. & Hid.	$3(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{1/2}+3(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{-1/2}$
Hidden	$14(\mathbf{1},\mathbf{2})_{0}+10(\overline{\mathbf{4}},\mathbf{1})_{0}+6(\mathbf{4},\mathbf{1})_{0}+3(\mathbf{6},\mathbf{1})_{0}+2(\mathbf{4},\mathbf{2})_{0}+71(\mathbf{1})_{0}$
Observable	$(\mathbf{1},\mathbf{2})_{-1/2}$ $(\mathbf{3},\mathbf{1})_{1/6}+(\overline{\mathbf{3}},\mathbf{1})_{-1/6}+2(\overline{\mathbf{3}},\mathbf{1})_{1/3}+13(\mathbf{1},\mathbf{2})_{0}+20(\mathbf{1},\mathbf{1})_{-1/2}+18(\mathbf{1},\mathbf{1})_{1/2}$
Obs. & Hid.	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{1/2}+(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{-1/2}+(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{0}$
Hidden	$14(\mathbf{1},\mathbf{2})_{0}+4(\mathbf{4},\mathbf{1})_{0}+(\mathbf{6},\mathbf{2})_{0}+23(\mathbf{1})_{0}$

This model with gauge groups $G_{\text{obs}} = \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$, $G_{\text{hid}} = \text{SU}(4) \times \text{SU}(2)$:

- contains vector-like fermionic and bosonic exotics
- in particular there are states that are charged under both the hidden and the SM gauge group.

Summary

We investigate smooth and orbifold compactifications of the non-supersymmetric heterotic SO(16)$\times$SO(16) string.

On smooth Calabi-Yau backgrounds we could recycle

- commonly employed techniques to determine both the fermionic and bosonic 4D spectra
- and argue that the N=0 theory never leads to tachyons on smooth Calabi-Yaus.

However, twisted tachyons may arise on certain singular orbifolds.

We have performed SM-like model searches on selected orbifold geometries and found over 12 thousand SM-like theories

Outlook

There are various very serious open issues:

- The Higgs mass will be quadratically dependent on the high scale
- The cosmological constant will be of the order of the string scale
- Associated with the cosmological constant, a destabilizing dilaton tadpole will be generated
- Tachyons may arise perturbatively and non-perturbatively