Non-Supersymmetric Heterotic Model Building

Orestis Loukas

Arnold Sommerfeld Center for Theoretical Physics
Ludwig-Maximilians-University, Munich

based on

JHEP10(2014)119(arXiv:1407.6362)

together with

Michael Blaszczyk (Mainz)
Stefan Groot Nibbelink (Munich)
Saul Ramos-Sánchez (Mexico)

Overview

1. Non-SUSY SO$(16)\times$SO(16)
    - Motivation
    - 10D formulation
    - Orbifolds of SO(16)×SO(16)
    - $\mathcal{N}=0$ model building
2. Non-SUSY smooth compactifications
    - CY threefolds
    - (No) tachyons
3. Conclusion & outlook

Heterotic SUSY: Review

- Conventional approach to systematic SUSY model-building

  Anderson,Blaszczyk,Bouchard,Braun,Buchmuller,Donagi,Gray,Groot Nibbelink,He,Kim,Lebedev,OL,Lukas,Nilles,Oehlmann,Ovrut,Ramos-Sánchez,Ratz,Rühle,Trapletti,Vaudrevange,Wingerter...

Heterotic SUSY: Review

- Conventional approach to systematic SUSY model-building

  Anderson,Blaszczyk,Bouchard,Braun,Buchmuller,Donagi,Gray,Groot Nibbelink,He,Kim,Lebedev,OL,Lukas,Nilles,Oehlmann,Ovrut,Ramos-Sánchez,Ratz,Rühle,Trapletti,Vaudrevange,Wingerter...

  - begin with $E_8 \times E_8$ on SUSY preserving compactification e.g. orbifolds, CY, non-geometric constructions...
  - look for MSSM-like models
  - introduce ~~SUSY~~ to obtain SM-like model

Motivation: Where is SUSY?

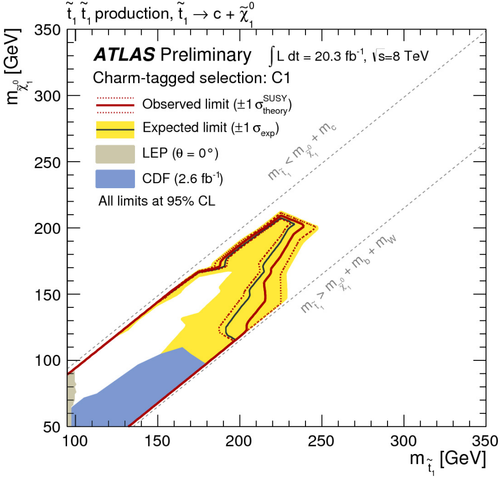


Figure : ATLAS analysis on experimental bounds for stop and neutralino masses,
published 20 July 2013

Motivation: Where is SUSY?

- Search for non-SUSY string models

Motivation: Where is SUSY?

- Search for non-SUSY string models
- Previous studies
  - Free fermionic construction with non-SUSY B.C.
    Dienes'94,'06, Faraggi,Tsulaia'07
  - Non-SUSY orbifolds of heterotic theories
    Chamseddine,Derendinger,Quiros'88, Taylor'88, Toon'90, Sasada'95, Font,Hernandez'02
  - Non-SUSY orientifold of type II theories
    Sagnotti'95, Angelantonj'98 Blumenhagen,Font,Luest'99, Aldazabal,Ibanez,Quevedo'99
  - Non-SUSY RCFT's
    Gato-Rivera,Schellekens'07

Heterotic $SO(16)\times SO(16)$

- **Tachyon-free** & **Anomaly-free** 10D non-SUSY heterotic theory
  Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

Heterotic SO(16)×SO(16)

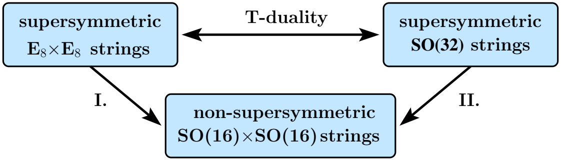
- **Tachyon-free** & **Anomaly-free** 10D non-SUSY heterotic theory
  Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

Massless Fields	Bosons	G_{MN}, B_{MN}, ϕ	Graviton, Kalb-Ramond 2-form, dilaton
		A_M	Gauge bosons of SO(16)×SO(16)
	Fermions	Ψ_+	Spinors in (**128**,**1**) and (**1**,**128**)
		Ψ_-	Cospinors in (**16**,**16**)

Heterotic SO(16)×SO(16)

- **Tachyon-free** & **Anomaly-free** 10D non-SUSY heterotic theory
  Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

Massless Fields	Bosons	G_{MN}, B_{MN}, ϕ	Graviton, Kalb-Ramond 2-form, dilaton
		A_M	Gauge bosons of SO(16)×SO(16)
	Fermions	Ψ_+	Spinors in (**128**,**1**) and (**1**,**128**)
		Ψ_-	Cospinors in (**16**,**16**)



supersymmetric
$E_8 \times E_8$ strings

T-duality

supersymmetric
SO(32) strings

I.

II.

non-supersymmetric
SO(16)×SO(16) strings

Heterotic (toroidal) orbifolds

- Begin with 10D heterotic theory

Left-movers	Right-movers	
X_L^μ	$(X_R^\mu,\, \Psi_R^\mu)$	$\mu = 0, ..., 9$
X_L^I	–	$I = 1, ..., 16$

Heterotic (toroidal) orbifolds

- Begin with 10D heterotic theory

Left-movers	Right-movers	
X_L^μ	$(X_R^\mu,\ \Psi_R^\mu)$	$\mu = 0, ..., 9$
X_L^I	–	$I = 1, ..., 16$

- 6D internal space on T^6

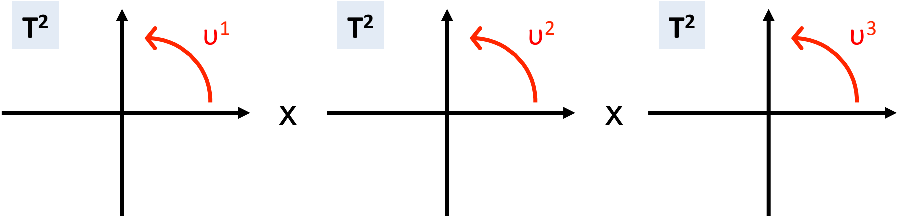
Heterotic (toroidal) orbifolds

- Begin with 10D heterotic theory

Left-movers	Right-movers	
X_L^μ	$(X_R^\mu,\ \Psi_R^\mu)$	$\mu = 0, ..., 9$
X_L^I	–	$I = 1, ..., 16$

- 6D internal space on T^6

- Identification $z^i \sim \mathrm{e}^{2\pi i v^i} z^i$ on T^6 by twist vector $v = (0, v_1, v_2, v_3)$



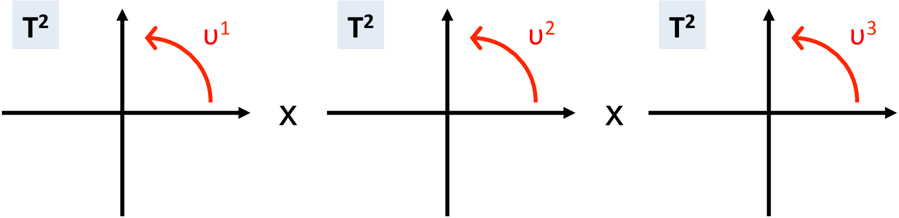
Heterotic (toroidal) orbifolds

- Begin with 10D heterotic theory

Left-movers	Right-movers	
X_L^μ	(X_R^μ, Ψ_R^μ)	$\mu = 0, ..., 9$
X_L^I	–	$I = 1, ..., 16$

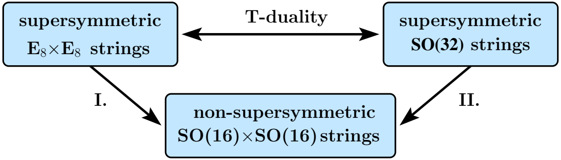
- 6D internal space on T^6

- Identification $z^i \sim \mathrm{e}^{2\pi i \upsilon^i} z^i$ on T^6 by twist vector $\upsilon = (0, \upsilon_1, \upsilon_2, \upsilon_3)$



- Shift on gauge 16-torus by V: $X_L^I \sim X_L^I + \pi V^I$

10D formulation of $SO(16)\times SO(16)$



supersymmetric
$E_8\times E_8$ strings

T-duality

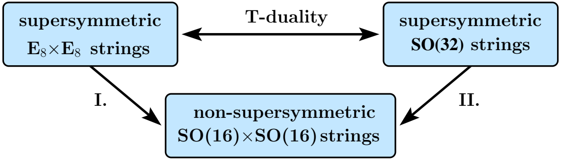
supersymmetric
SO(32) strings

I.

II.

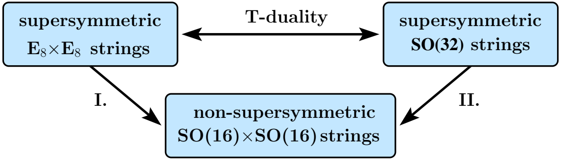
non-supersymmetric
$SO(16)\times SO(16)$ strings

10D formulation of SO$(16)\times$SO(16)



- Fermions Ψ_R respond to 2π twist by acquiring (-1)

10D formulation of SO$(16)\times$SO(16)



supersymmetric $E_8\times E_8$ strings

T-duality

supersymmetric SO(32) strings

I.

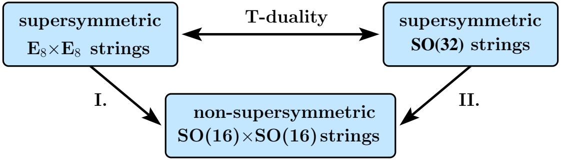
II.

non-supersymmetric SO(16)×SO(16) strings

- Fermions Ψ_R respond to 2π twist by acquiring (-1)

  $\Rightarrow$ twist GSO to kill space-time SUSY $\Rightarrow$ ~~SUSY~~ at tree level

10D formulation of SO$(16)\times$SO(16)



supersymmetric
$\mathbf{E_8\times E_8}$ strings

T-duality

supersymmetric
SO(32) strings

I.

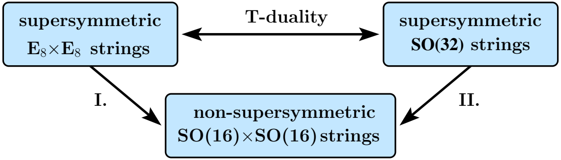
II.

non-supersymmetric
SO(16)$\times$SO(16) strings

- Fermions Ψ_R respond to 2π twist by acquiring (-1)

  $\Rightarrow$ twist GSO to kill space-time SUSY $\Rightarrow$ ~~SUSY~~ at tree level
- Orbifold-like construction, e.g. orbifold of E$_8\times$E$_8$

10D formulation of SO(16)×SO(16)



supersymmetric $E_8 \times E_8$ strings

T-duality

supersymmetric SO(32) strings

I.

II.

non-supersymmetric SO(16)×SO(16) strings

- Fermions Ψ_R respond to 2π twist by acquiring (-1)

  $\Rightarrow$ twist GSO to kill space-time SUSY $\Rightarrow$ ~~SUSY~~ at tree level

- Orbifold-like construction, e.g. orbifold of $E_8 \times E_8$

  $\Rightarrow$ freely acting ~~SUSY~~ $\mathbb{Z}_2$ moding with

$$v_0 = (0,1,1,1) \quad \text{and} \quad V_0 = (1,0^7)(1,0^7)'$$

Orbifolds of SO(16)×SO(16)

- For phenomenology we want to compactify down to 4D using toroidal orbifolds

Orbifolds of $\mathrm{SO}(16)\times\mathrm{SO}(16)$

- For phenomenology we want to compactify down to 4D using toroidal orbifolds
- Singular geometries **not** *preserving* SUSY
  - more than $29,100,000$
  - a full classification lacking, but in principle straightforward

Orbifolds of SO(16)×SO(16)

- For phenomenology we want to compactify down to 4D using toroidal orbifolds
- Singular geometries **not** *preserving* SUSY
  - more than $29,100,000$
  - a full classification lacking, but in principle straightforward
- Choose SUSY-*preserving* singular geometries
  - well-studied, exploit previous techniques
  - abelian symmetric toroidal orbifolds fully classified
    Fischer,Ratz,Torrado,Vaudrevange'12
  - **gain computational control**

Orbifolds of SO(16)×SO(16)

- We may think of construction as $\mathbb{Z}_2 \times \mathbb{Z}_N \times \mathbb{Z}_M$ orbifold of $\mathrm{E}_8\times\mathrm{E}_8$

Orbifolds of SO(16)×SO(16)

- We may think of construction as $\mathbb{Z}_2 \times \mathbb{Z}_N \times \mathbb{Z}_M$ orbifold of $E_8 \times E_8$
  - Compactify $E_8 \times E_8$ using

$$v_g = l v_0 + k v$$
$$V_g = l V_0 + k V$$

with $v_0 = (0, 1, 1, 1)$ $\mathbb{Z}_2$ ~~SUSY~~ twist

with $\sum v_i = 0$ $\mathbb{Z}_N$ SUSY twist

$k = 0, ..., N - 1$

Orbifolds of SO(16)×SO(16)

- We may think of construction as $\mathbb{Z}_2 \times \mathbb{Z}_N \times \mathbb{Z}_M$ orbifold of E$_8$×E$_8$
  - Compactify E$_8$×E$_8$ using

$$\boxed{\begin{aligned} v_g &= l v_0 + k v \\ V_g &= l V_0 + k V \end{aligned}}$$

with $v_0 = (0,1,1,1)$ $\mathbb{Z}_2$ ~~SUSY~~ twist

with $\sum v_i = 0$ $\mathbb{Z}_N$ SUSY twist

$k = 0, ..., N-1$

  - Same consistency conditions as in SUSY case from orbifold periodicity and modular invariance

$$N v \in \mathbb{Z}^4 \ , \quad N V \in \mathrm{E}_8\times\mathrm{E}_8 \ ,$$

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

Orbifolds of SO(16)×SO(16)

- We may think of construction as $\mathbb{Z}_2 \times \mathbb{Z}_N \times \mathbb{Z}_M$ orbifold of E$_8$×E$_8$
  - Compactify E$_8$×E$_8$ using

$$v_g = l v_0 + k v$$
$$V_g = l V_0 + k V$$

with $v_0 = (0,1,1,1)$ $\mathbb{Z}_2$ ~~SUSY~~ twist

with $\sum v_i = 0$ $\mathbb{Z}_N$ SUSY twist

$k = 0, ..., N-1$

  - Same consistency conditions as in SUSY case from orbifold periodicity and modular invariance

$$N v \in \mathbb{Z}^4 \ , \quad N V \in \text{E}_8\times\text{E}_8 \ ,$$
$$\tfrac{N}{2}(V^2 - v^2) \equiv 0 \ , \quad V \cdot V_0 \equiv 0$$

  - Include $\mathbb{Z}_N \times \mathbb{Z}_M$ orbifolds and Wilson lines

Orbifolds of SO(16)×SO(16): Tachyons

- Tachyons from twisted right-movers

Orbifolds of SO(16)×SO(16): Tachyons

- Tachyons from twisted right-movers

Orbifold	Twist	Tachyons	Orbifold	Twist	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			

Orbifolds of SO(16)×SO(16): Tachyons

- Tachyons from twisted right-movers

Orbifold	Twist	Tachyons	Orbifold	Twist	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			

- When tachyons possible in a geometry, not all models tachyonic, some of the tachyons remain unlevel-matched or are killed by orbifold projection

$\mathcal{N} = 0$ heterotic model building

- Look for SM-like models

$\mathcal{N} = 0$ heterotic model building

- Look for SM-like models
  - Only massless spectrum
  - Standard Model gauge group

$\mathcal{N} = 0$ heterotic model building

- Look for SM-like models
  - Only massless spectrum
  - Standard Model gauge group
  - Matter spectrum

Fermions	Bosons
Net number three of SM-families	At least one Higgs doublet
Vector-like pairs of exotics	Scalar exotics unconstrained

$\mathcal{N} = 0$ heterotic model building

- Look for SM-like models
  - Only massless spectrum
  - Standard Model gauge group
  - Matter spectrum

Fermions	Bosons
Net number three of SM-families	At least one Higgs doublet
Vector-like pairs of exotics	Scalar exotics unconstrained

- Equivalency of two models at the level of non-Abelian representations

$\mathcal{N}=0$ heterotic model building

- An example of one-Higgs SM-like model with gauge group

$$G_{\text{obs}} = SU(3)_C \times SU(2)_L \times U(1)_Y \quad \text{and} \quad G_{\text{hidden}} = SU(4)' \times SU(2)'$$

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	$14(\mathbf{1},\mathbf{2})_{0}+10(\overline{\mathbf{4}},\mathbf{1})_{0}+6(\mathbf{4},\mathbf{1})_{0}+4(\mathbf{6},\mathbf{1})_{0}+2(\mathbf{4},\mathbf{2})_{0}+71(\mathbf{1})_{0}$
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	$14(\mathbf{1},\mathbf{2})_{0}+4(\mathbf{4},\mathbf{1})_{0}+(\mathbf{6},\mathbf{2})_{0}+23(\mathbf{1})_{0}$

$\mathcal{N} = 0$ heterotic model building: Results

- Results from a first approach scan using modified version of *The Orbifolder* Nilles,Ramos-Sánchez,Vaudrevange,Wingerter'11

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

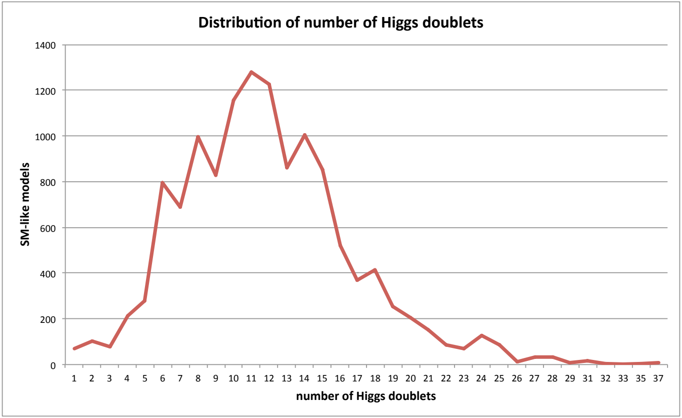
$\mathcal{N} = 0$ heterotic model building: Results

- Results from a first approach scan using modified version of *The Orbifolder* Nilles,Ramos-Sánchez,Vaudrevange,Wingerter'11

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

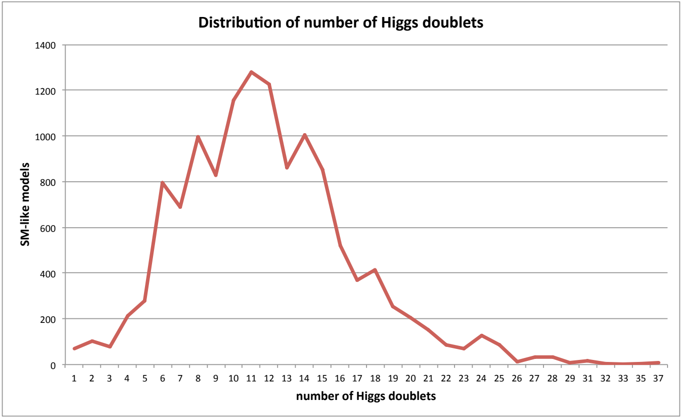
$\mathcal{N} = 0$ heterotic model building: Results

- Results from a first approach scan using modified version of *The Orbifolder* Nilles,Ramos-Sánchez,Vaudrevange,Wingerter'11



$\mathcal{N}=0$ heterotic model building: Results

- Results from a first approach scan using modified version of *The Orbifolder* Nilles,Ramos-Sánchez,Vaudrevange,Wingerter'11



SO(16)×SO(16) on CY

- On arbitrary smooth manifold
    - difficult to compute index of bosons
    - not clear how to deal with tachyons

SO(16)×SO(16) on CY

- On arbitrary smooth manifold
  - difficult to compute index of bosons
  - not clear how to deal with tachyons
- On $\mathcal{N} = 1$ CY threefolds

SO(16)×SO(16) on CY

- On arbitrary smooth manifold
  - difficult to compute index of bosons
  - not clear how to deal with tachyons
- On $\mathcal{N} = 1$ CY threefolds
  - exploit background SUSY to compute 4D massless spectrum for fermions & bosons

    e.g. using index theorems for fermions

SO(16)×SO(16) on CY

- On arbitrary smooth manifold
  - difficult to compute index of bosons
  - not clear how to deal with tachyons
- On $\mathcal{N} = 1$ CY threefolds
  - exploit background SUSY to compute 4D massless spectrum for fermions & bosons

    e.g. using index theorems for fermions
  - in particular for bosons, Laplace operator $\Delta \sim (\ i \not{D}\ )^2$

    $\Rightarrow$ bosonic spectrum bounded from below

SO(16)×SO(16) on CY: No tachyons

- What happens with orbifold tachyons?

SO(16)×SO(16) on CY: No tachyons

- What happens with orbifold tachyons?
- Consider particular example: $\boldsymbol{T^6}/\mathbb{Z}_{\text{6-I}}$ orbifold of $\mathcal{N} = 0$ theory

Non-Abelian gauge group: SU(5)×SU$(4)'$×SO$(4)'$×SU$(2)'$	
States	Representations of massless spectrum
Bosonic tachyons	$3\ (\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})$
Massless chiral fermions	$4(\mathbf{10};\mathbf{1}) + (\overline{\mathbf{10}};\mathbf{1}) + 6(\mathbf{5};\mathbf{1}) + 3(\overline{\mathbf{5}};\mathbf{1}) + (\mathbf{5};\mathbf{1},\mathbf{4},\mathbf{1}) + 2(\overline{\mathbf{5}};\mathbf{1},\mathbf{1},\mathbf{2}) + (\mathbf{5};\mathbf{1},\mathbf{1},\mathbf{2})$ $+2(\overline{\mathbf{5}};\mathbf{4},\mathbf{1},\mathbf{1}) + 12(\mathbf{1};\mathbf{4},\mathbf{1},\mathbf{1}) + 18(\mathbf{1};\overline{\mathbf{4}},\mathbf{1},\mathbf{1}) + 2(\mathbf{1};\overline{\mathbf{4}},\mathbf{2}_-,\mathbf{2}) + 2(\mathbf{1};\mathbf{4},\mathbf{2}_+,\mathbf{1})$ $+(\mathbf{1};\mathbf{6},\mathbf{2}_-,\mathbf{1}) + (\mathbf{1};\mathbf{6},\mathbf{2}_+,\mathbf{1}) + 12(\mathbf{1};\mathbf{1},\mathbf{2}_+,\mathbf{2}) + 4(\mathbf{1};\mathbf{1},\mathbf{4},\mathbf{1}) + 36(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1})$ $+30(\mathbf{1};\mathbf{1},\mathbf{2}_+,\mathbf{1}) + 11(\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2}) + 53(\mathbf{1};\mathbf{1})$
Massless complex scalars	$9(\mathbf{5};\mathbf{1}) + 2(\overline{\mathbf{5}};\mathbf{1}) + (\overline{\mathbf{10}};\mathbf{1}) + (\mathbf{1};\mathbf{1},\mathbf{4},\mathbf{2}) + 30(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1}) + 12(\mathbf{1};\mathbf{6},\mathbf{1},\mathbf{1})$ $+2(\mathbf{1};\mathbf{4},\mathbf{1},\mathbf{2}) + 2(\mathbf{1},\overline{\mathbf{4}},\mathbf{4},\mathbf{1}) + 22(\mathbf{1};\mathbf{1},\mathbf{2}_+,\mathbf{1}) + 10(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{2}) + 46(\mathbf{1};\mathbf{1})$

SO(16)×SO(16) on CY: No tachyons

- What happens with orbifold tachyons?
- Consider particular example: $\boldsymbol{T^6}/\mathbb{Z}_{\text{6-I}}$ orbifold of $\mathcal{N} = 0$ theory

Non-Abelian gauge group: SU(5)×SU$(4)'$×SO$(4)'$×SU$(2)'$	
States	Representations of massless spectrum
Bosonic tachyons	$3\ (\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})$
Massless chiral fermions	$4(\mathbf{10};\mathbf{1}) + (\overline{\mathbf{10}};\mathbf{1}) + 6(\mathbf{5};\mathbf{1}) + 3(\overline{\mathbf{5}};\mathbf{1}) + (\mathbf{5};\mathbf{1},\mathbf{4},\mathbf{1}) + 2(\overline{\mathbf{5}};\mathbf{1},\mathbf{1},\mathbf{2}) + (\mathbf{5};\mathbf{1},\mathbf{1},\mathbf{2})$ $+2(\overline{\mathbf{5}};\mathbf{4},\mathbf{1},\mathbf{1}) + 12(\mathbf{1};\mathbf{4},\mathbf{1},\mathbf{1}) + 18(\mathbf{1};\overline{\mathbf{4}},\mathbf{1},\mathbf{1}) + 2(\mathbf{1};\overline{\mathbf{4}},\mathbf{2}_-,\mathbf{2}) + 2(\mathbf{1};\mathbf{4},\mathbf{2}_+,\mathbf{1})$ $+(\mathbf{1};\mathbf{6},\mathbf{2}_-,\mathbf{1}) + (\mathbf{1};\mathbf{6},\mathbf{2}_+,\mathbf{1}) + 12(\mathbf{1};\mathbf{1},\mathbf{2}_+,\mathbf{2}) + 4(\mathbf{1};\mathbf{1},\mathbf{4},\mathbf{1}) + 36(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1})$ $+30(\mathbf{1};\mathbf{1},\mathbf{2}_+,\mathbf{1}) + 11(\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2}) + 53(\mathbf{1};\mathbf{1})$
Massless complex scalars	$9(\mathbf{5};\mathbf{1}) + 2(\overline{\mathbf{5}};\mathbf{1}) + (\overline{\mathbf{10}};\mathbf{1}) + (\mathbf{1};\mathbf{1},\mathbf{4},\mathbf{2}) + 30(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1}) + 12(\mathbf{1};\mathbf{6},\mathbf{1},\mathbf{1})$ $+2(\mathbf{1};\mathbf{4},\mathbf{1},\mathbf{2}) + 2(\mathbf{1},\overline{\mathbf{4}},\mathbf{4},\mathbf{1}) + 22(\mathbf{1};\mathbf{1},\mathbf{2}_+,\mathbf{1}) + 10(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{2}) + 46(\mathbf{1};\mathbf{1})$

- Resolution of this model by standard techniques
  Lüst,Reffert,Scheidegger,Stieberger'08, Groot Nibbelink,Nilles,Trapletti'08

SO(16)×SO(16) on CY: No tachyons

State	Sector	Representation
Tachyon t	θ^1	$(\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})$
Blow-up mode b	θ^2	$(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1})$

$$V(t,b) = \ -m_t^2|t|^2 \ + \ |\lambda|^2|b|^2|t|^2 \ + \mathcal{O}(b^4,t^4)$$

SO(16)×SO(16) on CY: No tachyons

State	Sector	Representation
Tachyon t	θ^1	$(\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})$
Blow-up mode b	θ^2	$(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1})$

$$V(t,b) = \; -m_t^2|t|^2 \;\; + \; |\lambda|^2|b|^2|t|^2 \;\; + \mathcal{O}(b^4,t^4)$$

- Field-theoretical Motivation

SO(16)×SO(16) on CY: No tachyons

State	Sector	Representation
Tachyon t	θ^1	$(\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})$
Blow-up mode b	θ^2	$(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1})$

$$V(t,b) = \ -m_t^2|t|^2 \ + \ |\lambda|^2|b|^2|t|^2 \ + \mathcal{O}(b^4,t^4)$$

- Field-theoretical Motivation
  - sign ambiguity of 2nd term
  - on CY Δ-spectrum non-negative

    $\Rightarrow$ ambiguous sign has to be "$+$"

SO(16)×SO(16) on CY: No tachyons

State	Sector	Representation
Tachyon t	θ^1	$(\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})$
Blow-up mode b	θ^2	$(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1})$

$$V(t,b) = \; -m_t^2|t|^2 \; + \; |\lambda|^2|b|^2|t|^2 \; + \mathcal{O}(b^4,t^4)$$

- Field-theoretical Motivation
  - sign ambiguity of 2nd term
  - on CY Δ-spectrum non-negative

    $\Rightarrow$ ambiguous sign has to be "$+$"
- In large volume limit tachyon gets lifted
  - $|b|^2 \sim \text{Vol}(E_r) \gg M_s^2 \sim |m_t|^2$

Conclusions & Outlook

- Non-SUSY SO$(16)$$\times$SO$(16)$

Conclusions & Outlook

- Non-SUSY SO$(16)\times$SO(16)
- Constructed more than 12000 SM-like models on selected orbifold geometries

Conclusions & Outlook

- Non-SUSY SO$(16)\times$SO(16)
- Constructed more than 12000 SM-like models on selected orbifold geometries
- Non-SUSY theory on $\mathcal{N}=1$ smooth geometries
  - No tree-level tachyons in large volume limit

Conclusions & Outlook

- Non-SUSY SO$(16)\times$SO(16)
- Constructed more than 12000 SM-like models on selected orbifold geometries
- Non-SUSY theory on $\mathcal{N}=1$ smooth geometries
  - No tree-level tachyons in large volume limit
- Basic issues with non-SUSY models:
  - Tachyons can get induced by α' and g_s corrections

Conclusions & Outlook

- Non-SUSY SO$(16)\times$SO(16)
- Constructed more than 12000 SM-like models on selected orbifold geometries
- Non-SUSY theory on $\mathcal{N}=1$ smooth geometries
  - No tree-level tachyons in large volume limit
- Basic issues with non-SUSY models:
  - Tachyons can get induced by α' and g_s corrections
  - Cosmological constant Λ and destabilizing dilaton tadpole

Conclusions & Outlook

- Some future directions:
  - Systematic non-SUSY model searches on smooth CY's
    e.g. CICY, with (line) bundles
    Work in progress...

Conclusions & Outlook

- Some future directions:
  - Systematic non-SUSY model searches on smooth CY's
    e.g. CICY, with (line) bundles
    Work in progress...
  - Investigate perturbative as well as non-perturbative generation of tachyons
    e.g. how $\mathcal{N} = 0$ theory reacts in presence of NS5-brane

Conclusions & Outlook

- Some future directions:
  - Systematic non-SUSY model searches on smooth CY's
    e.g. CICY, with (line) bundles
    Work in progress...
  - Investigate perturbative as well as non-perturbative generation of tachyons
    e.g. how $\mathcal{N} = 0$ theory reacts in presence of NS5-brane
  - Investigate the cosmological constant issue in non-SUSY string models
    Angelantonj,Florakis,Tsulaia'14, Abel,Dienes,Mavroudi'15

10D formulation of SO(16)×SO(16)

Lattices in the theory	
N=1, E_8×E_8	N=0, SO(16)×SO(16)
$\mathbf{V}_4 \otimes \mathbf{R}_8 \otimes \mathbf{R}_8$	$\mathbf{V}_4 \otimes \mathbf{R}_8 \otimes \mathbf{R}_8$
$\mathbf{V}_4 \otimes \mathbf{S}_8 \otimes \mathbf{S}_8$	$\mathbf{V}_4 \otimes \mathbf{S}_8 \otimes \mathbf{S}_8$
$\mathbf{V}_4 \otimes \mathbf{S}_8 \otimes \mathbf{R}_8$	$\mathbf{R}_4 \otimes \mathbf{C}_8 \otimes \mathbf{V}_8$
$\mathbf{V}_4 \otimes \mathbf{R}_8 \otimes \mathbf{S}_8$	$\mathbf{R}_4 \otimes \mathbf{V}_8 \otimes \mathbf{C}_8$
$\mathbf{S}_4 \otimes \mathbf{S}_8 \otimes \mathbf{R}_8$	$\mathbf{S}_4 \otimes \mathbf{S}_8 \otimes \mathbf{R}_8$
$\mathbf{S}_4 \otimes \mathbf{R}_8 \otimes \mathbf{S}_8$	$\mathbf{S}_4 \otimes \mathbf{R}_8 \otimes \mathbf{S}_8$
$\mathbf{S}_4 \otimes \mathbf{R}_8 \otimes \mathbf{R}_8$	$\mathbf{C}_4 \otimes \mathbf{V}_8 \otimes \mathbf{V}_8$
$\mathbf{S}_4 \otimes \mathbf{S}_8 \otimes \mathbf{S}_8$	$\mathbf{C}_4 \otimes \mathbf{C}_8 \otimes \mathbf{C}_8$

SO(16)×SO(16) on CY's

- On arbitrary smooth manifold difficult to compute index of bosons

SO(16)×SO(16) on CY's

- On arbitrary smooth manifold difficult to compute index of bosons
- On $\mathcal{N} = 1$ CY threefolds exploit background SUSY to compute 4D massless spectrum, in particular

SO(16)×SO(16) on CY's

- On arbitrary smooth manifold difficult to compute index of bosons
- On $\mathcal{N} = 1$ CY threefolds exploit background SUSY to compute 4D massless spectrum, in particular

Massless fermions

- spinors in (**128**,**1**) and (**1**,**128**)
- cospinors in (**16**,**16**)

Massless bosons

- Gravity sector
- (**120**,**1**) and (**1**,**120**) adjoint

SO(16)×SO(16) on CY's

- On arbitrary smooth manifold difficult to compute index of bosons
- On $\mathcal{N} = 1$ CY threefolds exploit background SUSY to compute 4D massless spectrum, in particular

Massless fermions

- spinors in (**128**,**1**) and (**1**,**128**)
- cospinors in (**16**,**16**)

Massless bosons

- Gravity sector
- (**120**,**1**) and (**1**,**120**) adjoint

- Standard index theorems to determine multiplicity of 4D fermions

SO(16)×SO(16) on CY's

- On arbitrary smooth manifold difficult to compute index of bosons
- On $\mathcal{N} = 1$ CY threefolds exploit background SUSY to compute 4D massless spectrum, in particular

Massless fermions

- spinors in $(\mathbf{128},\mathbf{1})$ and $(\mathbf{1},\mathbf{128})$
- cospinors in $(\mathbf{16},\mathbf{16})$

Massless bosons

- Gravity sector
- $(\mathbf{120},\mathbf{1})$ and $(\mathbf{1},\mathbf{120})$ adjoint

- Standard index theorems to determine multiplicity of 4D fermions
- To calculate multiplicities of 4D bosons, use index of their fermionic superpartners, before the latter are projected out by ~~SUSY~~ $\mathbb{Z}_2$

10D formulation of SO$(16)\times$SO(16)

	Massless Fields	10D Space-time interpretation
Bosons	G_{MN}, B_{MN}, ϕ	Graviton, Kalb-Ramond 2-form, dilaton
	A_M	Gauge bosons of SO(16)×SO(16)
Fermions	Ψ_+	Spinors in (**128**,**1**) and (**1**,**128**)
	Ψ_-	Cospinors in (**16**,**16**)

- Bosons and Spinors come from untwisted sector of $\mathbb{Z}_2^{\cancel{\text{SUSY}}}$
- Cospinors come from twisted sector of $\mathbb{Z}_2^{\cancel{\text{SUSY}}}$

$\mathcal{N} = 0$ heterotic model building

- Computer-aided scans in SM-landscape
  - modified version of *The Orbifolder* using orbifold formulation

    Nilles,Ramos-Sánchez,Vaudrevange,Wingerter'11
  - anomaly cancellation in 4D

$\mathcal{N} = 0$ heterotic model building

- Computer-aided scans in SM-landscape
  - modified version of *The Orbifolder* using orbifold formulation
    Nilles,Ramos-Sánchez,Vaudrevange,Wingerter'11
  - anomaly cancellation in 4D
- Further consistency checks
  - independent *Mathematica* code using torsion phase formulation
  - matching spectra with resolved models (see below)

Heterotic SO$(16)\times$SO(16)

- 10D non-SUSY superstring theory: SO$(16)\times$SO(16)

Heterotic $\mathrm{SO}(16)\times\mathrm{SO}(16)$

- 10D non-SUSY superstring theory: $\mathrm{SO}(16)\times\mathrm{SO}(16)$
- Relation to both heterotic $\mathrm{E}_8\times\mathrm{E}_8$ and SO(32)

Heterotic SO$(16)\times$SO(16)

- 10D non-SUSY superstring theory: SO$(16)\times$SO(16)
- Relation to both heterotic $\mathrm{E}_8\times\mathrm{E}_8$ and SO(32)
- To see this at the level of partition function of either standard heterotic theory:
  - introduce modular invariant non-SUSY generalized discrete torsion phases or equivalently
  - perform 10D orbifold-like construction to break SUSY

$\Rightarrow$ SUSY broken already at tree level

SO(16)×SO(16) on CY: (No) tachyons

- On $\mathcal{N} = 1$ CY we can avoid tachyons by working in large volume approximation

SO(16)×SO(16) on CY: (No) tachyons

- On $\mathcal{N} = 1$ CY we can avoid tachyons by working in large volume approximation
- Evidence for no tachyons on CY's with a vector bundle:
  - In general, the reduction of 10D bosonic action on CY uses only the bosonic lowest component of superfields, whose fermionic part maybe projected out by ~~SUSY~~ $\mathbb{Z}_2$

SO(16)×SO(16) on CY: (No) tachyons

- On $\mathcal{N}=1$ CY we can avoid tachyons by working in large volume approximation
- Evidence for no tachyons on CY's with a vector bundle:
  - In general, the reduction of 10D bosonic action on CY uses only the bosonic lowest component of superfields, whose fermionic part maybe projected out by ~~SUSY~~ $\mathbb{Z}_2$
  - Zero modes of Laplace opetator determine massless bosons

$$\Delta \sim (iD)^2 \;\longrightarrow\; \Delta\text{-spectrum is non-negative}$$

SO(16)×SO(16): Open questions

- BUT
  - orbifold tachyons can get induced by α' and g_s corrections

SO(16)×SO(16): Open questions

- BUT
  - orbifold tachyons can get induced by α' and g_s corrections
- However in SM we need negative Higgs mass for EWSB
  - MSSM: $m_h < 0$ induced by ~~SUSY~~, hierarchy problem
  - $\mathcal{N} = 0$ models: similar problem, just enhanced by $\frac{M_s}{m_{\cancel{SUSY}}} < 10^{13}$

SO(16)×SO(16): Open questions

- BUT
  - orbifold tachyons can get induced by α' and g_s corrections
- However in SM we need negative Higgs mass for EWSB
  - MSSM: $m_h < 0$ induced by ~~SUSY~~, hierarchy problem
  - $\mathcal{N} = 0$ models: similar problem, just enhanced by $\frac{M_s}{m_{\cancel{SUSY}}} < 10^{13}$
- Cosmological constant Λ and destabilizing dilaton tadpole
  - in general value of Λ finite but not $\sim$ zero
  - contributions to Λ of tachyons and tower of massive states

Heterotic SUSY: Review

- Why SUSY?
  - hierarchy problem, Higgs mass
  - unification of gauge couplings
  - dark matter candidate
  - compelling extension of Poincaré group
  - **gain computational control**

Motivation

- General non-SUSY geometric backgrounds for heterotic orbifolds
  - 370 point groups representable by twist vectors
  - More than 7000 point groups with arbitrary geometric action, e.g. complex conjugation
  - More than $29,100,000$ corresponding geometric classes
  - Generically some 4D models will have unprojected tachyons
  - A full classification lacking, but in principle straightforward

Motivation

- General non-SUSY geometric backgrounds for heterotic orbifolds
  - 370 point groups representable by twist vectors
  - More than 7000 point groups with arbitrary geometric action, e.g. complex conjugation
  - More than $29,100,000$ corresponding geometric classes
  - Generically some 4D models will have unprojected tachyons
  - A full classification lacking, but in principle straightforward
- SO$(16)\times$SO(16) : 10D non-SUSY superstring theory
  - Tachyon-free
  - Anomaly-free
  - Relation to both heterotic $\mathrm{E}_8\times\mathrm{E}_8$ and SO(32)

Orbifolds of SO(16)×SO(16): Tachyons

- In twisted sector of 10D $\mathbb{Z}_2^{\cancel{\text{SUSY}}}$ unlevel-matched right-moving tachyon on SO$(8)_R$
- Tachyonic levels from twisted right-movers on root lattice SO$(8)_R$

Orbifolds of SO(16)×SO(16): Tachyons

- In twisted sector of 10D $\mathbb{Z}_2^{\cancel{\text{SUSY}}}$ unlevel-matched right-moving tachyon on $\text{SO}(8)_R$
- Tachyonic levels from twisted right-movers on root lattice $\text{SO}(8)_R$

  Consider $\omega = kv + q\ ,\ \ q \in \text{SO}(8)_R$ such that $0 \leq \omega_1 \leq \omega_2 \leq \frac{1}{2}$

R-movers mass on twisted $\text{SO}(8)_R$

$$M_R^2 = \omega_1 + \omega_2 - \frac{1}{2}$$

Orbifolds of SO(16)×SO(16): Tachyons

- In twisted sector of 10D $\mathbb{Z}_2^{\cancel{\text{SUSY}}}$ unlevel-matched right-moving tachyon on $\text{SO}(8)_R$
- Tachyonic levels from twisted right-movers on root lattice $\text{SO}(8)_R$

  Consider $\omega = kv + q\ ,\ \ q \in \text{SO}(8)_R$ such that $0 \leq \omega_1 \leq \omega_2 \leq \frac{1}{2}$

R-movers mass on twisted $\text{SO}(8)_R$

$$M_R^2 = \omega_1 + \omega_2 - \frac{1}{2}$$

- At most one tachyonic level possible

Orbifolds of SO(16)×SO(16): Tachyons

- In twisted sector of 10D $\mathbb{Z}_2^{\cancel{\text{SUSY}}}$ unlevel-matched right-moving tachyon on SO$(8)_R$
- Tachyonic levels from twisted right-movers on root lattice SO$(8)_R$

  Consider $\omega = kv + q\ ,\ \ q \in \text{SO}(8)_R$ such that $0 \leq \omega_1 \leq \omega_2 \leq \frac{1}{2}$

R-movers mass on twisted SO$(8)_R$

$$M_R^2 = \omega_1 + \omega_2 - \frac{1}{2}$$

- At most one tachyonic level possible
- In contrast to $\mathcal{N} = 1$, massless right-moving excitations possible

Orbifolds of SO(16)×SO(16): Tachyons

- In twisted sector of 10D $\mathbb{Z}_2^{\cancel{\text{SUSY}}}$ unlevel-matched right-moving tachyon on $\text{SO}(8)_R$
- Tachyonic levels from twisted right-movers on root lattice $\text{SO}(8)_R$

  Consider $\omega = kv + q \ , \ \ q \in \text{SO}(8)_R$ such that $0 \leq \omega_1 \leq \omega_2 \leq \frac{1}{2}$

R-movers mass on twisted $\text{SO}(8)_R$

$$M_R^2 = \omega_1 + \omega_2 - \frac{1}{2}$$

- At most one tachyonic level possible
- In contrast to $\mathcal{N} = 1$, massless right-moving excitations possible
- In some twists, tachyonic levels also from excited R-movers

Computer-aided model building

- SO(16)×SO(16)-like non-SuSy twists

$$\boxed{\frac{N}{2}v = (0,1,1,1) = v_0}$$

Computer-aided model building

- SO(16)×SO(16)-like non-SuSy twists

$$\boxed{\frac{N}{2}v = (0,1,1,1) = v_0}$$

- Two model-independently tachyon-free non-SUSY geometries $v_4 = (0, \frac{1}{2}, \frac{1}{2}, \frac{1}{2})$ and $v_6 = (0, \frac{1}{3}, \frac{1}{3}, \frac{1}{3})$

- Results from a first approach scan

Orbifold		Inequivalent	Tachyon-free	SM-like tachyon-free models		
twist	#(geom)	scanned models	percentage	total	one-Higgs	two-Higgs
v_4	(1)		100 %		0	0
v_6	(1)	1226676	100 %	1146	177	15

SO(16)×SO(16) on CY: The Standard embedding

- Gauge embedding of spin structure already gives an **SO(10) GUT**:

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

SO(16)×SO(16) on CY: The Standard embedding

- Gauge embedding of spin structure already gives an **SO(10) GUT**:

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

- 4D spectrum via standard cohomology theory as in SUSY-case

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

SO(16)×SO(16) on CY: The Standard embedding

- Gauge embedding of spin structure already gives an **SO(10) GUT**:

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

- 4D spectrum via standard cohomology theory as in SUSY-case

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

- Net number of **16** of SO(10) determined by $h^{1,1} - h^{2,1}$

SO(16)×SO(16) on CY: Line Bundles

- Work on same $\mathcal{N} = 1$ backgrounds, all previous tools applicable

SO(16)×SO(16) on CY: Line Bundles

- Work on same $\mathcal{N} = 1$ backgrounds, all previous tools applicable
- In particular,

Massless fermions

- spinors in $(\mathbf{128},\mathbf{1})$ and $(\mathbf{1},\mathbf{128})$
- cospinors in $(\mathbf{16},\mathbf{16})$

Massless bosons

- Gravity sector
- $(\mathbf{120},\mathbf{1})$ and $(\mathbf{1},\mathbf{120})$ adjoint

SO(16)×SO(16) on CY: Line Bundles

- Work on same $\mathcal{N} = 1$ backgrounds, all previous tools applicable
- In particular,

Massless fermions

- spinors in $(\mathbf{128},\mathbf{1})$ and $(\mathbf{1},\mathbf{128})$
- cospinors in $(\mathbf{16},\mathbf{16})$

Massless bosons

- Gravity sector
- $(\mathbf{120},\mathbf{1})$ and $(\mathbf{1},\mathbf{120})$ adjoint

  - Index of fermions as before
  - Use projected out superpartners from $\mathbf{S}_4 \otimes \mathbf{R}_8 \otimes \mathbf{R}_8$ to compute index of bosons from $\mathbf{V}_4 \otimes \mathbf{R}_8 \otimes \mathbf{R}_8$

SO(16)×SO(16) on CY: Orbifold Resolutions

- Application: Line bundle models on the resolution of $\boldsymbol{T^6}/\mathbb{Z}_3$
  Luest,Reffert,Scheidegger,Stieberger'08, Groot-Nibbelink,Nilles,Trapletti'08

SO(16)×SO(16) on CY: Orbifold Resolutions

- Application: Line bundle models on the resolution of $\boldsymbol{T^6}/\mathbb{Z}_\mathbf{3}$
  Luest,Reffert,Scheidegger,Stieberger'08, Groot-Nibbelink,Nilles,Trapletti'08
  - Abelian gauge flux: $\frac{\mathcal{F}}{2\pi} = H_I W_I^r E_r$
  - Integrated Bianchi identities: $W_r^2 = \frac{4}{3}$
  - DUY condition: $\int \frac{\mathcal{F}}{2\pi} \in \mathbf{R}_8 \otimes \mathbf{R}_8$ ($\notin$ E$_8$×E$_8$)

SO(16)×SO(16) on CY: Orbifold Resolutions

- Application: Line bundle models on the resolution of $\boldsymbol{T^6}/\mathbb{Z}_3$
  Luest,Reffert,Scheidegger,Stieberger'08, Groot-Nibbelink,Nilles,Trapletti'08
  - Abelian gauge flux: $\frac{\mathcal{F}}{2\pi} = H_I W_I^r E_r$
  - Integrated Bianchi identities: $W_r^2 = \frac{4}{3}$
  - DUY condition: $\int \frac{\mathcal{F}}{2\pi} \in \mathbf{R}_8 \otimes \mathbf{R}_8$ ($\notin$ E$_8$×E$_8$)

Line bundle vector W Gauge group G	Massless spectrum in blow-up: chiral fermions / complex bosons
$\frac{1}{3}(0,2^3,0^4)\,(0^8)$	$3(\mathbf{3},\mathbf{1};\mathbf{16})_2 + 3(\overline{\mathbf{3}},\overline{\mathbf{16}};\mathbf{1})_1 + 27(\mathbf{1},\overline{\mathbf{16}};\mathbf{1})_{\text{-}3}$
U(3)×SO(10)×SO(16)'	$78(\overline{\mathbf{3}},\mathbf{1};\mathbf{1})_4 + 3(\mathbf{3},\mathbf{10};\mathbf{1})_2$
$\frac{1}{3}(1^6,0^2)\,(1^6,0^2)$	$3(\overline{\mathbf{6}},\mathbf{2}_-;\mathbf{1})_{\text{-}2} + 3(\mathbf{1};\overline{\mathbf{6}},\mathbf{2}_-)_{\text{-}2} + 3(\mathbf{15},\mathbf{2}_+;\mathbf{1})_1 + 3(\mathbf{1};\mathbf{15},\mathbf{2}_+)_1 + 3(\overline{\mathbf{6}},\mathbf{1};\overline{\mathbf{6}},\mathbf{1})_2$
	$+3(\mathbf{6},\mathbf{1};\mathbf{1},\mathbf{4})_{\text{-}1} + 3(\mathbf{1},\mathbf{4};\mathbf{6},\mathbf{1})_{\text{-}1} + 27(\mathbf{1},\mathbf{2}_+;\mathbf{1})_{\text{-}3} + 27(\mathbf{1};\mathbf{1},\mathbf{2}_+)_{\text{-}3}$
U(6)×SO(4)×U(6)'×SO(4)'	$3(\overline{\mathbf{15}},\mathbf{1};\mathbf{1})_2 + 3(\mathbf{1};\overline{\mathbf{15}},\mathbf{1})_2 + 3(\mathbf{6},\mathbf{4};\mathbf{1})_{\text{-}1} + 3(\mathbf{1};\mathbf{6},\mathbf{4})_{\text{-}1}$
$\frac{1}{3}(1^8)\,(1^4,0^4)$	$3(\mathbf{8};\mathbf{1},\mathbf{8}_v)_{\text{-}1} + 3(\mathbf{1};\mathbf{1},\mathbf{8}_s)_{\text{-}2} + 3(\mathbf{1};\mathbf{4},\mathbf{8}_c)_1 + 3(\overline{\mathbf{28}};\mathbf{1})_{\text{-}2}$
	$+3(\overline{\mathbf{8}};\overline{\mathbf{4}},\mathbf{1})_2 + 78(\mathbf{1};\mathbf{1})_{\text{-}4}$
U(8)×U(4)'×SO(8)'	$3(\overline{\mathbf{28}};\mathbf{1})_2 + 3(\mathbf{1};\mathbf{6},\mathbf{1})_2 + 3(\mathbf{1};\mathbf{4},\mathbf{8}_v)_{\text{-}1}$

SO(16)×SO(16) on CY: (No) Tachyons

- On arbitrary $\mathcal{N} = 1$ CY we can avoid tachyons by working in large volume approximation

SO(16)×SO(16) on CY: (No) Tachyons

- On arbitrary $\mathcal{N} = 1$ CY we can avoid tachyons by working in large volume approximation
- Evidence for no tachyons on CY's with a vector bundle:
  - Zero modes of Laplace opetator determine massless bosons

$$\Delta \sim (iD)^2 \;\longrightarrow\; \Delta\text{-spectrum is non-negative}$$

SO(16)×SO(16) on CY: (No) Tachyons

- On arbitrary $\mathcal{N} = 1$ CY we can avoid tachyons by working in large volume approximation
- Evidence for no tachyons on CY's with a vector bundle:
  - Zero modes of Laplace opetator determine massless bosons

    $$\Delta \sim (iD)^2 \;\longrightarrow\; \Delta\text{-spectrum is non-negative}$$

  - F- and D-terms govern the scalar potential to leading order

    $$V = \sum_a \left|\frac{\partial \mathcal{W}}{\partial Z^a}\right|^2 + \frac{1}{2}D^2 \;\longrightarrow\; \text{non-negative contributions}$$

    where Z^a would-be chiral extension to massless complex scalars

  - Form of V justified since the reduction of 10D bosonic action on CY uses only the bosonic lowest component of Z^a

The End