Non-supersymmetric heterotic model building

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based on

arXiv:1407.6362

together with:

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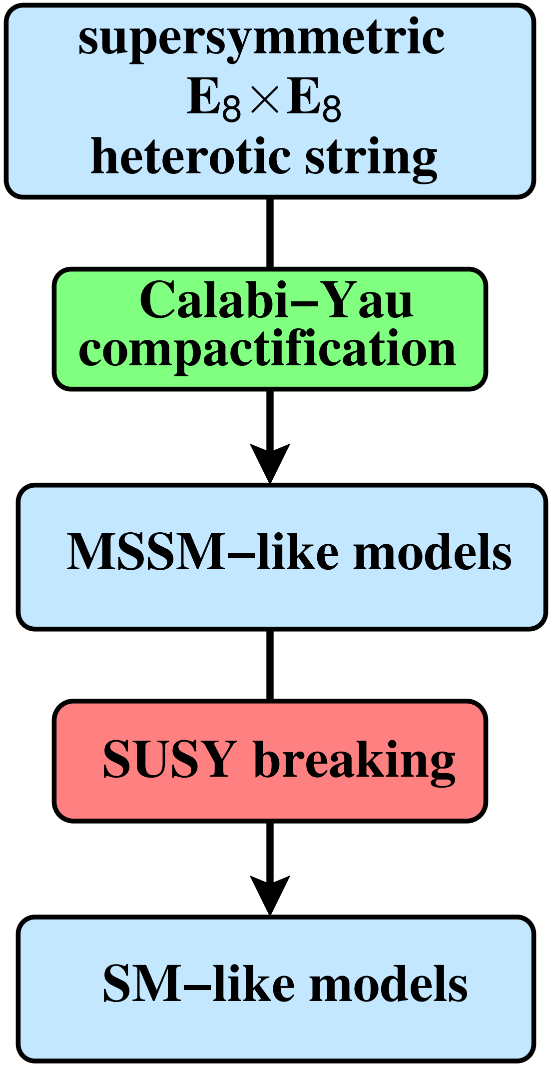
Saul Ramos-Sánchez (Mexico)

Overview of this talk

The conventional heterotic route towards SM



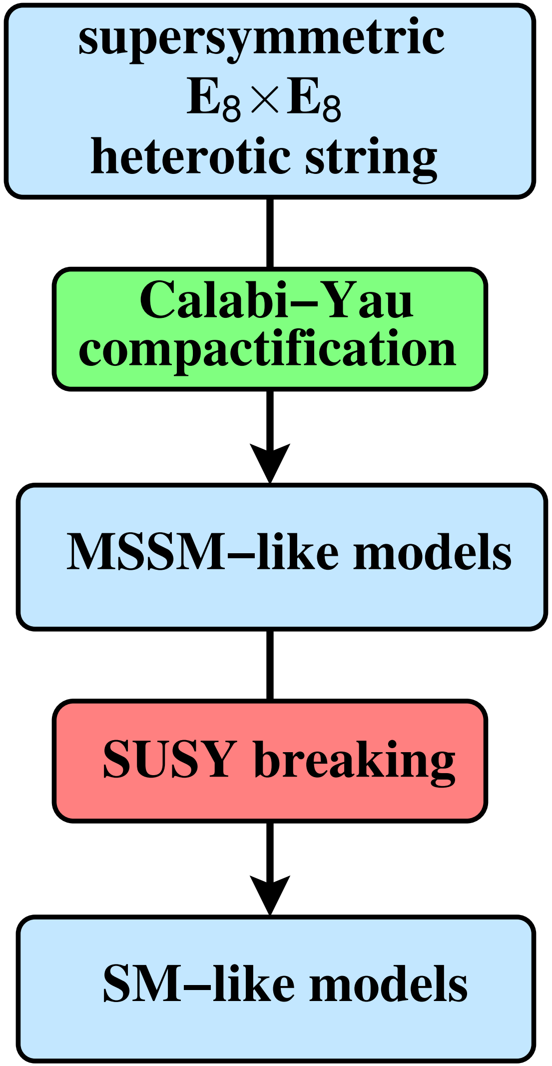
assumes an intermediate MSSM, i.e.:

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

and subsequently some mechanism of SUSY breaking, i.e.:

- order hundred soft parameters
- induced by gauge, gravity, anomaly mediations

The conventional heterotic route towards SM



supersymmetric
$E_8 \times E_8$
heterotic string

Calabi–Yau compactification

MSSM–like models

SUSY breaking

SM–like models

obtains 4D MSSM-like models via compactification one has to carefully choose a string background, i.e.:

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

- a complicated six dimensional Calabi-Yau manifold $\mathcal{M}^6$;
  Candelas,Horowitz,Strominger,Witten'85
- supporting a suitable stable holomorphic vector bundle

  (the standard embedding $E_8 \to E_6$ leads to a problematic GUT)
- or toroidal orbifolds Dixon,Harvey, Vafa,Witten'85, Ibanez,Mas,Nilles,Quevedo'87

Recent model building results

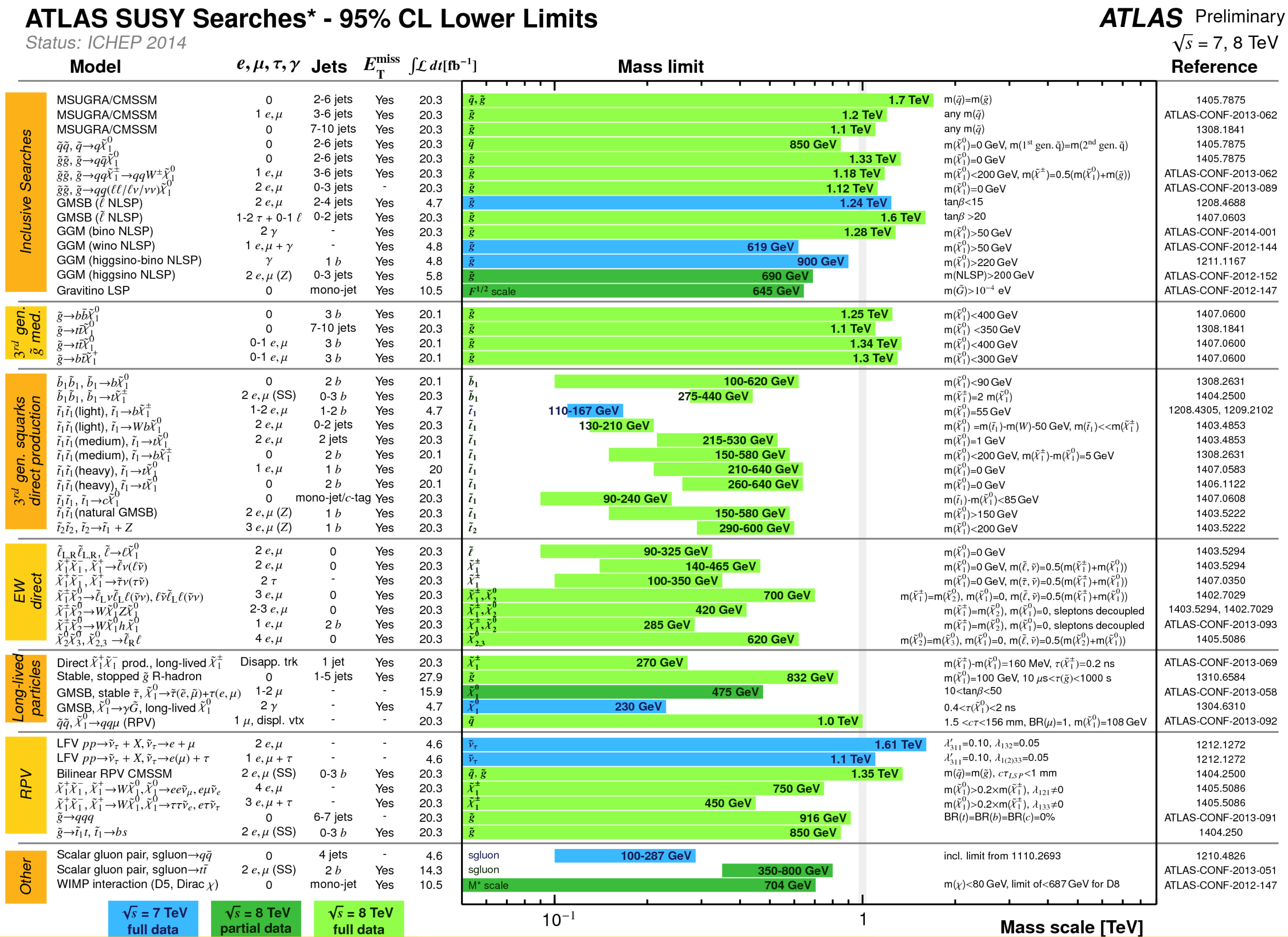
MSSM–like models on Calabi–Yaus:

- 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: Vaudrevange,Nilles'14

- $T^6/\mathbb{Z}_{\text{6-II}}$ 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
- $T^6/\mathbb{Z}_{\text{8-I,II}}$ SGN,Loukas'13

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	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	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
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1^{st} gen. $\tilde{\mathrm{q}}$)=m(2^{nd} gen. $\tilde{\mathrm{q}}$)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	m($\tilde{\chi}_1^0$)=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($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>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
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<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($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<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($\tilde{\chi}_1^0$)>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($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=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	$\tilde{\chi}_1^\pm$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 285 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_{\mathrm{R}}\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=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($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{121}\neq 0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq 0$	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

$\sqrt{s}$ = 7 TeV full data

$\sqrt{s}$ = 8 TeV partial data

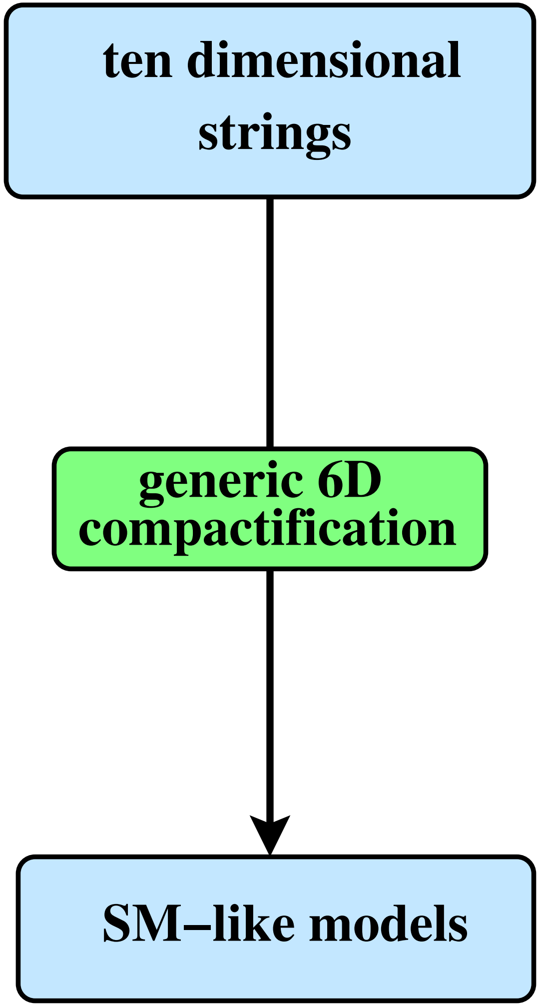
$\sqrt{s}$ = 8 TeV full data

Why do (did) we believe in supersymmetry?

Some motivations for supersymmetry:

- hierarchy problem
- unification of gauge couplings
- dark matter candidate
- compelling extension of the Poincaré group
- **gain computational control**

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



ten dimensional strings

generic 6D compactification

SM–like models

Non-SUSY string models have:

- hierarchy problem
- unstable Higgs mass
- large cosmological constant
- with associated dilaton tadpole
- **tachyons are possible**
- **far less computational control**

Generic 6D compactifications are:

- unclassified number of manifolds
- even the number of toroidal orbifolds is almost 29 million

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

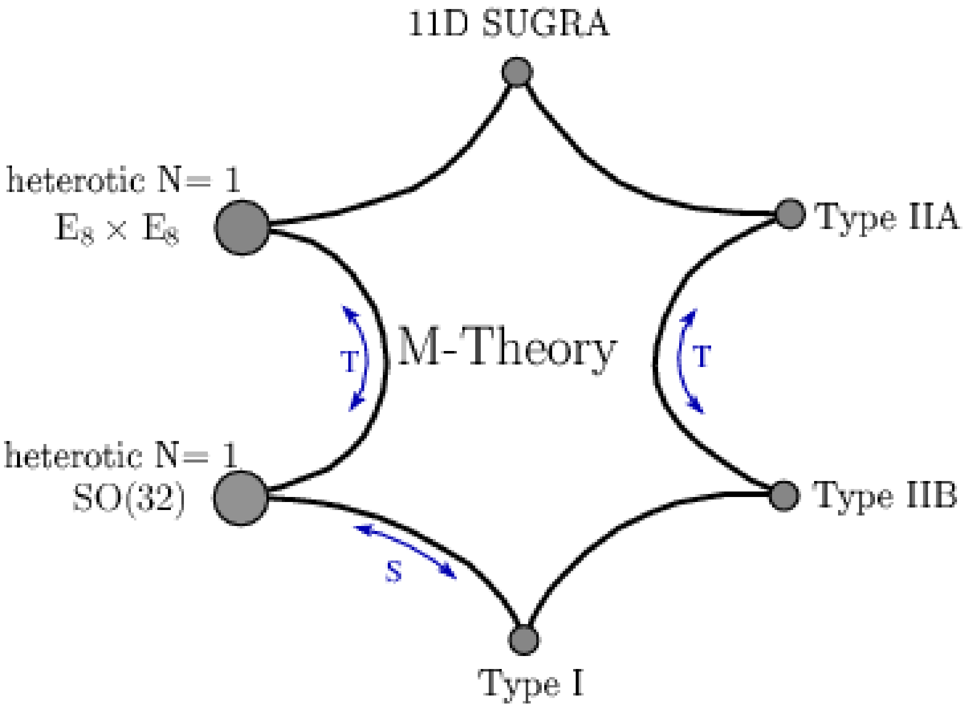
  Chamseddine,Derendinger,Quiros'88, Taylor'88, Toon'90, Sasada'95, Font,Hernandez'02
- Non-supersymmetric orientifold type II theories

  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 an interesting heterotic string theory...

The non-supersymmetric heterotic string

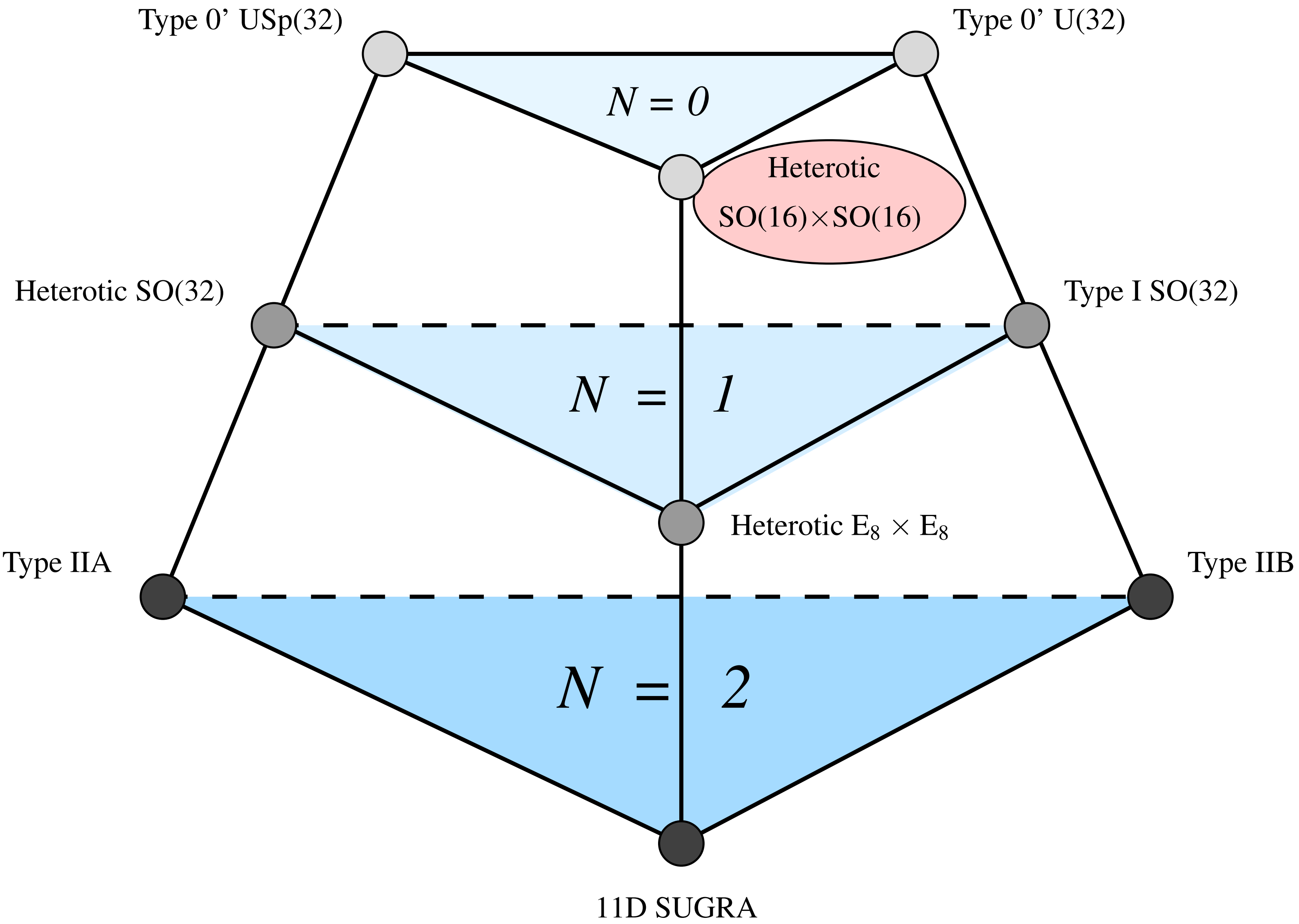
The low-energy spectrum of the N=0 heterotic string reads:

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)×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



Two constructions of the SO(16)×SO(16) string

The non-supersymmetric heterotic SO(16)×SO(16) string is closely related to the supersymetric heterotic $E_8\times E_8$ string:

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

- **I. SUSY breaking torsion phases:**

  Their partition functions are identical up to generalized torsion T between the various spin structures $(s, t, \ldots)$

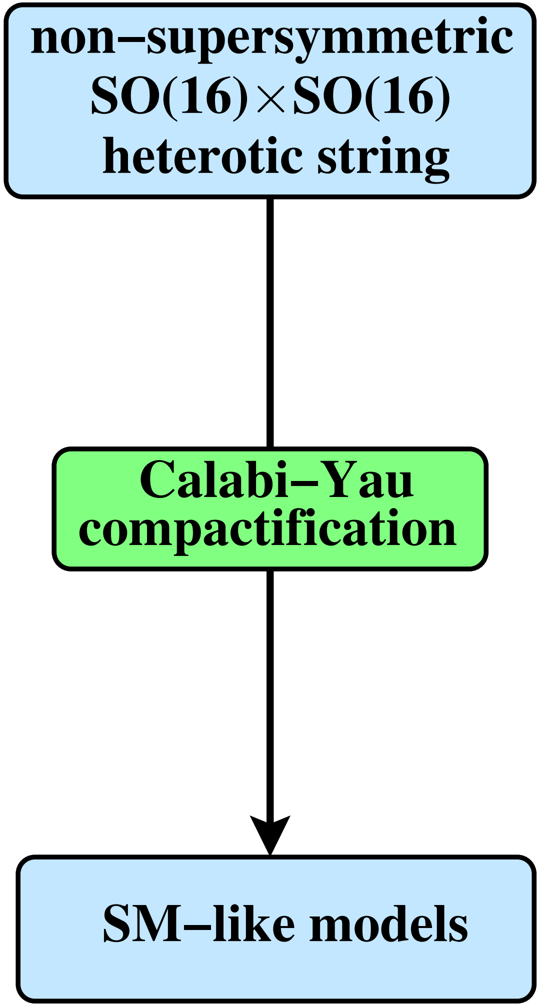
$$T = (-)^{st'-s't} * \ldots$$

- **II. SUSY breaking orbifold:**

  The SO(16)×SO(16) theory is a $\mathbb{Z}_2$ "orbifold" of the $E_8\times E_8$ string twist v_0 and gauge shift V_0:

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

Smooth Calabi-Yau compactifications



non–supersymmetric SO(16)×SO(16) heterotic string

Calabi–Yau compactification

SM–like models

We could compactify the N=0 theory on any smooth 6D manifold, but then we loose any computation control...

We will consider smooth compactifications which would themselves preserve supersymmetry, i.e.:

Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

- holomorphic vector bundles on Calabi-Yau manifolds
- subject to the Bianchi identities:

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

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: SGN,Trapletti,Walter'07

$$\mathcal{N} = \int \frac{1}{6}\left(\frac{\mathcal{F}_2}{2\pi}\right)^3 - \frac{1}{24}\,\frac{\mathcal{F}_2}{2\pi}\,\mathrm{tr}\left(\frac{\mathcal{R}_2}{2\pi}\right)^2$$

evaluated on all fermionic states:

fermions	Ψ_+	Spinors in the $(\mathbf{128},\mathbf{1})+(\mathbf{1},\mathbf{128})$
	Ψ_-	Cospinors in the $(\mathbf{16},\mathbf{16})$

Computation of the bosonic spectrum

On a generic six-manifold I do not 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 for complex scalars

$$\Delta \sim (i\not{D})^2$$

is related to the Dirac operator $i\not{D}$ of the would be gaugino:

bosons	A_M	SO(16)×SO(16) Adjoint gauge fields

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

No tachyons on Calabi-Yau backgrounds

To leading order there are no tachyon on smooth Calabi-Yau backgrounds in the large volume approximation:

Since on smooth Calabi-Yau backgrounds the Laplace operator Δ is related to the square of the Dirac operator $i\not{D}$, its spectrum is non-negative

Hence a major problem of non-supersymmetric model building, tachyons, can be avoided by working on smooth Calabi-Yaus

Scalar potential on Calabi-Yau backgrounds

To leading order the scalar potential V is determined by F- and D-terms as if the theory is supersymmetric:

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

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

This follows because the reduction of the 10D bosonic action on a Calabi-Yau with a vector bundle only uses the bosonic fields, for which this result holds

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

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

Line bundle models on $\mathbb{Z}_3$ orbifold resolutions

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)’	$78(\overline{\mathbf{3}},\mathbf{1};\mathbf{1})_{\text{-}4}+3(\mathbf{3},\mathbf{10};\mathbf{1})_{\text{-}2}$
$\frac{1}{3}(1^6,0^2)(1^6,0^2)$	$3(\overline{\mathbf{6}},\mathbf{2};\mathbf{1})_{\text{-}2}+3(\mathbf{1};\overline{\mathbf{6}},\mathbf{2})_{\text{-}2}+3(\mathbf{15},\mathbf{2};\mathbf{1})_1+3(\mathbf{1};\mathbf{15},\mathbf{2})_1$ $+3(\overline{\mathbf{6}},\mathbf{1};\overline{\mathbf{6}},\mathbf{1})_{\text{-}2}+3(\mathbf{6},\mathbf{1};\mathbf{1},\mathbf{4})_1+3(\mathbf{1},\mathbf{4};\mathbf{6},\mathbf{1})_1$ $+27(\mathbf{1},\mathbf{2};\mathbf{1})_{\text{-}3}+27(\mathbf{1};\mathbf{1},\mathbf{2})_{\text{-}3}$
U(6)×SO(4)×U(6)’×SO(8)’	$3(\overline{\mathbf{15}},\mathbf{1};\mathbf{1})_{\text{-}2}+3(\mathbf{1};\overline{\mathbf{15}},\mathbf{1})_{\text{-}2}+3(\mathbf{6},\mathbf{4};\mathbf{1})_1+3(\mathbf{1};\mathbf{6},\mathbf{4})_1$
$\frac{1}{3}(1^8)(1^4,0^4)$	$3(\mathbf{8};\mathbf{1},\mathbf{8}_v)_1+3(\mathbf{1};\mathbf{1},\mathbf{8}_s)_{\text{-}2}+3(\mathbf{1};\mathbf{4},\mathbf{8}_c)_1+3(\overline{\mathbf{28}};\mathbf{1})_{\text{-}2}$ $+3(\overline{\mathbf{8}};\overline{\mathbf{4}},\mathbf{1})_{\text{-}2}+78(\mathbf{1};\mathbf{1})_{\text{-}4}$
U(8)×U(4)’×SO(4)	$3(\overline{\mathbf{28}};\mathbf{1})_{\text{-}2}+3(\mathbf{1};\mathbf{6},\mathbf{1})_{\text{-}2}+3(\mathbf{1};\mathbf{4},\mathbf{8}_v)_1$

These bosonic and fermionic spectra:

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

Orbifolding the N=0 theory

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

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

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

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

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

Conditions from modular invariance

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

$$v = (v_1, v_2, -v_1 - v_2)\ , \quad \text{like} \quad (\tfrac{1}{3}, \tfrac{1}{3}, -\tfrac{2}{3}) \quad \text{for} \quad \mathbb{Z}_3$$

We require that we have modular invariant partition function for the orbifolded N=0 theory in the $\mathbb{Z}_2$ ”orbifold” formulation:

$$\frac{N}{2}(V^2 - v^2) \equiv V_0 \cdot V - v_0 \cdot v \equiv 0$$

with

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

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
$\frac{1}{3}(0, 1^2, -2, 0^4)(0^8)$	$3(\mathbf{3}, \mathbf{1}; \mathbf{16}) + 3(\overline{\mathbf{3}}, \overline{\mathbf{16}}; \mathbf{1}) + 27(\mathbf{1}, \overline{\mathbf{16}}; \mathbf{1}) + (\mathbf{1}, \overline{\mathbf{16}}; \mathbf{1})$ $+(\mathbf{1}, \mathbf{16}; \mathbf{1}) + (\mathbf{1}; \mathbf{128}) + (\mathbf{1}, \mathbf{10}; \mathbf{16}) + 27(\mathbf{1}; \mathbf{16})$
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 tachyons, non-Abelian anomalies and possess at most one universal anomalous U(1)

Twisted tachyons

Tachyons are possible in some twisted sectors of many orbifolds:

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

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

However, when tachyons are possible this does not mean that all such orbifold models actually will have tachyons

Twisted tachyons of a $\mathbb{Z}_{6\text{–I}}$ model in blow-up

The $\mathbb{Z}_{6\text{–I}}$ orbifold model spectrum has tachyons:

States	Gauge representations of the spectrum of a tachyonic $\mathbb{Z}_{6\text{-I}}$ orbifold
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	$9(\mathbf{5};\mathbf{1})+2(\overline{\mathbf{5}};\mathbf{1})+(\overline{\mathbf{10}};\mathbf{1})+(\mathbf{1};\mathbf{1},\mathbf{4},\mathbf{2})+30(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1})+12(\mathbf{1};\mathbf{6},\mathbf{1},\mathbf{1})$ $+2(\mathbf{1};\mathbf{4},\mathbf{1},\mathbf{2})+2(\mathbf{1},\overline{\mathbf{4}},\mathbf{4},\mathbf{1})+22(\mathbf{1};\mathbf{1},\mathbf{2}_+,\mathbf{1})+10(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{2})+46(\mathbf{1};\mathbf{1})$

but its full resolution is free of tachyons:

States	Non-Abelian representations of a blown-up tachyonic orbifold model
Bosonic tachyons	none
Massless chiral fermions	$3(\overline{\mathbf{10}};\mathbf{1})+3(\mathbf{5};\mathbf{1})+6(\overline{\mathbf{5}};\mathbf{1})+2(\overline{\mathbf{5}};\mathbf{1},\mathbf{2}_+)+2(\mathbf{5};\mathbf{2}_-,\mathbf{1})+2(\mathbf{5};\mathbf{2}_+,\mathbf{1})+(\mathbf{5};\mathbf{1},\mathbf{2}_-)$ $2(\mathbf{1};\mathbf{4},\mathbf{1})+2(\mathbf{1};\mathbf{1},\mathbf{4})+2(\mathbf{1};\mathbf{2}_+,\mathbf{2}_+)+4(\mathbf{1};\mathbf{2}_+,\mathbf{2}_-)+2(\mathbf{1};\mathbf{2}_-,\mathbf{2}_+)$ $4(\mathbf{1};\mathbf{2}_-,\mathbf{2}_-)+6(\mathbf{1};\mathbf{2}_+,\mathbf{1})+8(\mathbf{1};\mathbf{2}_-,\mathbf{1})+34(\mathbf{1};\mathbf{1},\mathbf{2}_+)+11(\mathbf{1};\mathbf{1},\mathbf{2}_-)+53(\mathbf{1};\mathbf{1})$
Massless complex scalars	$(\overline{\mathbf{10}};\mathbf{1})+9(\mathbf{5};\mathbf{1})+2(\overline{\mathbf{5}};\mathbf{1})+2(\mathbf{1};\mathbf{4},\mathbf{1})+2(\mathbf{1};\mathbf{1},\mathbf{4})$ $4(\mathbf{1};\mathbf{2}_+,\mathbf{2}_+)+2(\mathbf{1};\mathbf{2}_+,\mathbf{2}_-)+4(\mathbf{1};\mathbf{2}_-,\mathbf{2}_+)+2(\mathbf{1};\mathbf{2}_-,\mathbf{2}_-)+43(\mathbf{1};\mathbf{1})$

Orbifold SM-like model searches

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

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 theories

Orbifold		Inequivalent	Tachyon-free	SM-like tachyon-free models		
twist	#(geom)	scanned models	percentage	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 by implementing the SUSY breaking $\mathbb{Z}_2$ orbifolding of the $E_8 \times E_8$ theory in the ”Orbifolder package” (Nilles,Ramos-Sanchez, Vaudrevange,Wingerter’12)

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
- there are states that are charged under both the hidden and the SM gauge group

Summary

We have studied smooth and orbifold compactifications of the non-supersymmetric heterotic SO(16)×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; in full blow-up they disappear from the spectrum

We have performed SM-like model searches on selected orbifold geometries and found over 12,000 SM-like theories

Outlook

Some future directions:

- perform non-SUSY model searches on smooth Calabi-Yaus with (line) bundles
- Investigate the cosmological constant in non-SUSY string models
- Investigate the consequences of the destabilizing dilaton tadpole associated to the cosmological constant
- Investigate perturbative and non-perturbative generation of tachyons