Non-supersymmetric heterotic constructions

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Based on work together with:

Michael Blaszczyk (Mainz), Orestis Loukas (Bern),
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and publications:

JHEP 1410 (2014) 119 [arXiv:1407.6362]

DISCRETE'14 proceedings [arXiv:1502.03604]

JHEP 1510 (2015) 166 [arXiv:1507.06147]

Fortsch.Phys. 63 (2015) 609-632 [arXiv:1507.07559]

arXiv:1605.07470

Overview of this talk

1. Motivation
2. Non-supersymmetric heterotic strings
3. Effective Field Theory descriptions of non-susy strings
4. Calabi-Yau Compactifications
5. (0,2) aspects of non-SUSY heterotic strings

Main motivation: Where is Supersymmetry?

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

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

	Model	e,μ,τ,γ	Jets	E_T^{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
	$\tilde q\tilde q,\ \tilde q\to q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde q$ 850 GeV	$m(\tilde\chi_1^0)$=0 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	1405.7875
	$\tilde q\tilde q\gamma,\ \tilde q\to q\tilde\chi_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde q$ 250 GeV	$m(\tilde q)-m(\tilde\chi_1^0)=m(c)$	1411.1559
	$\tilde g\tilde g,\ \tilde g\to q\bar q\tilde\chi_1^0$	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	$\tilde g$ 1.2 TeV	$m(\tilde\chi_1^0)$<300 GeV, $m(\tilde\chi^\pm)=0.5(m(\tilde\chi_1^0)+m(\tilde g))$	1501.03555
	$\tilde g\tilde g,\ \tilde g\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde\chi_1^0$	2 e,μ	0-3 jets	-	20	$\tilde g$ 1.32 TeV	$m(\tilde\chi_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde\ell$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde g$ 1.6 TeV	$\tan\beta$>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	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde G)>1.8\times10^{-4}$ eV, $m(\tilde g)=m(\tilde q)$=1.5 TeV	1502.01518
3rd 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
3rd 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
	$\tilde t_1\tilde t_1,\ \tilde t_1\to b\tilde\chi_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde t_1$ 110-167 GeV; 230-460 GeV	$m(\tilde\chi_1^\pm)$ = 2$m(\tilde\chi_1^0)$, $m(\tilde\chi_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde t_1\tilde t_1,\ \tilde t_1\to Wb\tilde\chi_1^0$ or $t\tilde\chi_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde t_1$ 90-191 GeV; 215-530 GeV	$m(\tilde\chi_1^0)$=1 GeV	1403.4853, 1412.4742
	$\tilde t_1\tilde t_1,\ \tilde t_1\to t\tilde\chi_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde t_1$ 210-640 GeV	$m(\tilde\chi_1^0)$=1 GeV	1407.0583,1406.1122
	$\tilde t_1\tilde t_1,\ \tilde t_1\to c\tilde\chi_1^0$	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	$\tilde\ell_{L,R}\tilde\ell_{L,R},\ \tilde\ell\to\ell\tilde\chi_1^0$	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
	$\tilde\chi_1^\pm\tilde\chi_2^0\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu),\ \ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	20.3	$\tilde\chi_1^\pm,\tilde\chi_2^0$ 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
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0Z\tilde\chi_1^0$	2-3 e,μ	0-2 jets	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
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0h\tilde\chi_1^0,\ h\to b\bar b/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde\chi_1^\pm,\tilde\chi_2^0$ 250 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde\chi_2^0\tilde\chi_3^0,\ \tilde\chi_{2,3}^0\to\tilde\ell_R\ell$	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, $\tau(\tilde\chi_1^\pm)$=0.2 ns	1310.3675
	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<$\tau(\tilde g)$<1000 s	1310.6584
	Stable $\tilde g$ R-hadron	trk	-	-	19.1	$\tilde g$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde\tau,\ \tilde\chi_1^0\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde\chi_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde\chi_1^0\to\gamma\tilde G$, long-lived $\tilde\chi_1^0$	2 γ	-	Yes	20.3	$\tilde\chi_1^0$ 435 GeV	2<$\tau(\tilde\chi_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde q\tilde q,\ \tilde\chi_1^0\to qq\mu$ (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×$m(\tilde\chi_1^\pm)$, $\lambda_{121}\neq0$	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×$m(\tilde\chi_1^\pm)$, $\lambda_{133}\neq0$	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
	$\tilde g\to\tilde t_1t,\ \tilde t_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde g$ 850 GeV		1404.250
Other	Scalar charm, $\tilde c\to c\tilde\chi_1^0$	0	2 c	Yes	20.3	$\tilde c$ 490 GeV	$m(\tilde\chi_1^0)$<200 GeV	1501.01325

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

10^{-1} — 1 — Mass scale [TeV]

Main motivating questions:

- **So far no hints for supersymmetry found, what if this stays this way?**
- **What could that mean for string theory?**
- **How to describe supersymmetry breaking within string theory?**
- **Can one do string model building without supersymmetry?**

Possible scales of supersymmetry breaking:

In light of these bounds there are a couple of options:

- the supersymmetry breaking scale is around a few TeV
- the supersymmetry breaking scale is somewhere between the Planck and electroweak scale
- the supersymmetry breaking happens at the Planck/String scale, i.e. there is no supersymmetry in target space

In this talk we will mostly entertain the extreme case: Supersymmetry breaking at the string scale.

Past works on non-supersymmetric strings

- Non-supersymmetric (orbifolds of) heterotic theories

  Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86 Itoyahama,Taylor'87 Chamseddine,Derendinger,Quiros'88, Taylor'88, Toon'90, Sasada'95, Font,Hernandez'02

- Free fermionic construction with non-supersymmetric boundary conditions

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

- 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

Recent renewed heterotic interest

- Non-supersymmetric heterotic model building

  Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

- Towards a non-supersymmetric string phenomenology

  Abel,Dienses,Mavroudi'15

- Heterotic moduli stabilisation and non-supersymmetric vacua

  Lukas,Lalak,Svanes'15

- Non-tachyonic semi-realistic non-supersymmetric heterotic string vacua

  Ashfaque,Athanasopoulos,Faraggi,Sonmez'15

- Generalised universality of gauge thresholds in heterotic vacua with and without supersymmetry

  Angelantonj, Florakis, Tsulaia'15

Non-supersymmetric heterotic strings

10D (non-)supersymmetric heterotic strings

Dixon,Harvey'86

Heterotic theory	SUSY	Tachyons	Fermions
$E_8\times E_8$	yes	none	Superpartners
$Spin(32)/\mathbb{Z}_2$	yes	none	Superpartners
$SO(16)\times SO(16)$	no	none	$(\mathbf{128};\mathbf{1})_+ + (\mathbf{1};\mathbf{128})_+ + (\mathbf{16};\mathbf{16})_-$
$E_8\times SO(16)$	no	$(\mathbf{1};\mathbf{16})$	$(\mathbf{1};\mathbf{128}_+)_+ + (\mathbf{1};\mathbf{128}_-)_-$
$(E_7\times SU(2))^2$	no	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})$	$(\mathbf{56},\mathbf{2};\mathbf{1},\mathbf{1})_+ + (\mathbf{1},\mathbf{1};\mathbf{56},\mathbf{2})_+$ $(\mathbf{56},\mathbf{1};\mathbf{1},\mathbf{2})_- + (\mathbf{1},\mathbf{2};\mathbf{56},\mathbf{1})_-$
$SO(24)\times SO(8)$	no	$(\mathbf{1};\mathbf{8}_s)$	$(\mathbf{24};\mathbf{8})_+ + (\mathbf{24};\mathbf{8})_-$
$U(16)$	no	$(\mathbf{1}_{+4}) + (\mathbf{1}_{-4})$	$(\mathbf{120}_{+2})_+ + (\overline{\mathbf{120}}_{-2})_+$
$SO(32)$	no	$(\mathbf{32})$	none

By considering Scherk-Schwarz supersymmetry breaking and Wilson lines on circle (torus) compactifications, one can show that all these theories are continuously connected to each other

Ginsparg,Vafa'87, Nair,Sharpere,Strominger,Wilczek'87

The non-supersymmetric heterotic string

The low-energy spectrum of the non-supersymmetric tachyon-free SO(16)×SO(16) 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

Effective field Theory descriptions for non-supersymmetric heterotic strings

Do these non-supersymmetric string constructions possess special properties?

- **Possible hidden fermionic symmetries**
- **Quantum properties**
- **Others ???**

Hidden fermionic symmetries in non-supersymmetric heterotic theories?

$E_8 \times E_8$ and SO(16)×SO(16) Partition functions

The partition functions of the non-supersymmetric heterotic SO(16)×SO(16) and the supersymmetric heterotic $E_8 \times E_8$ strings are closely related: Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

Introduce SUSY breaking discrete torsion phases :

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

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

$$\mathbf{Z}_{SO(16)^2} = \sum_{\text{spin}} T \cdot \mathbf{Z}_8^x(\tau,\overline{\tau}) \cdot \widehat{\mathbf{Z}}_4 \left[{s \atop s'}\right](\tau) \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{t \atop t'}\right](\tau)} \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{u \atop u'}\right](\tau)}$$

with torsion phases Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

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

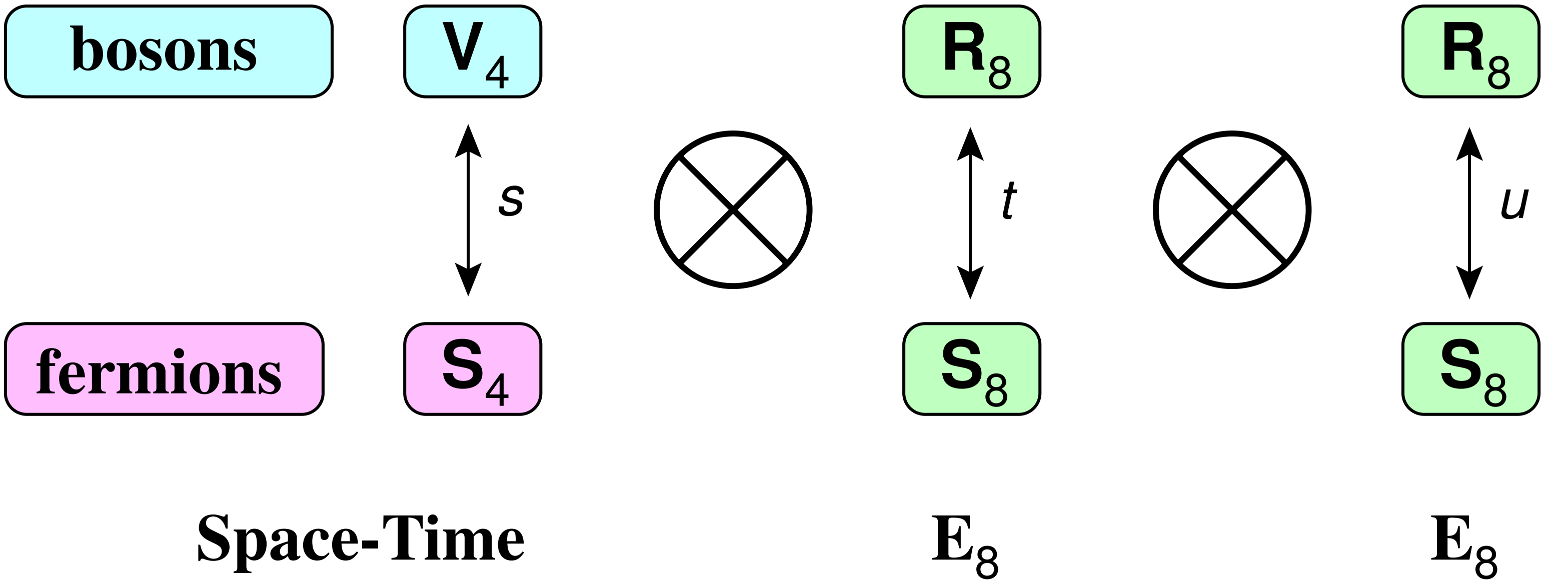
Heterotic weight lattices

The partition function can be viewed as lattice sums over the following lattices:

	Weight lattice	Lattice vectors	Lattice generators
$\mathbf{R}_D$	Root	$n \in \mathbb{Z}^D$, $\sum n_i \in 2\mathbb{Z}$	$\big(\underline{\pm 1^2, 0^{D-2}}\big)$
$\mathbf{V}_D$	Vector	$n \in \mathbb{Z}^D$, $\sum n_i \in 2\mathbb{Z}+1$	$\big(\underline{\pm 1, 0^{D-2}}\big)$
$\mathbf{S}_D$	Spinor	$n \in \mathbb{Z}^D + \frac{1}{2}e_D$, $\sum n_i \in 2\mathbb{Z}$	$\big(\underline{-\frac{1}{2}^{2n}, +\frac{1}{2}^{D-2n}}\big)$
$\mathbf{C}_D$	Cospinor	$n \in \mathbb{Z}^D + \frac{1}{2}e_D$, $\sum n_i \in 2\mathbb{Z}+1$	$\big(\underline{-\frac{1}{2}^{2n+1}, +\frac{1}{2}^{D-2n-1}}\big)$

Spin-structure *s* as supersymmetry generator

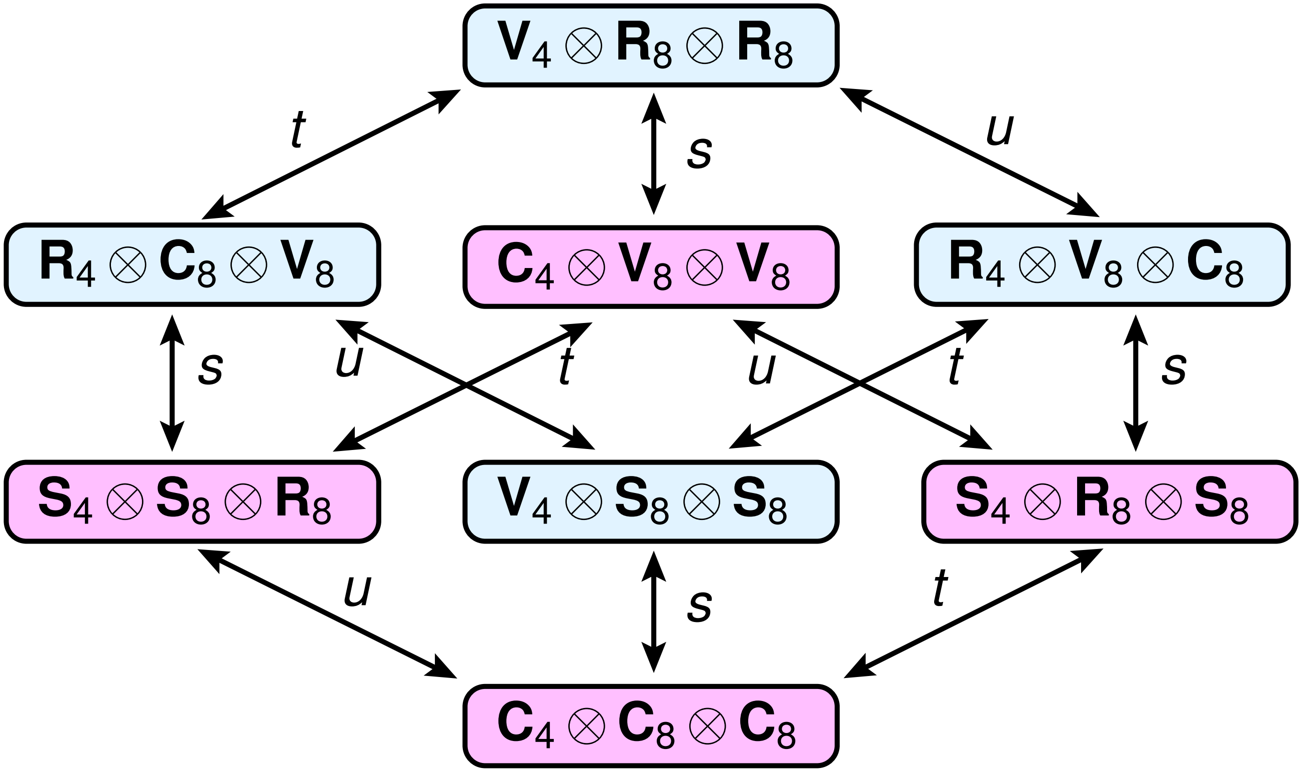
Standard $E_8 \times E_8$ theory:



Supersymmetry : $\delta_s A_M^\alpha = \Psi_+^\alpha \ , \qquad \alpha \in E_8 \oplus E_8$

Spin-structures as SUSY-like generators

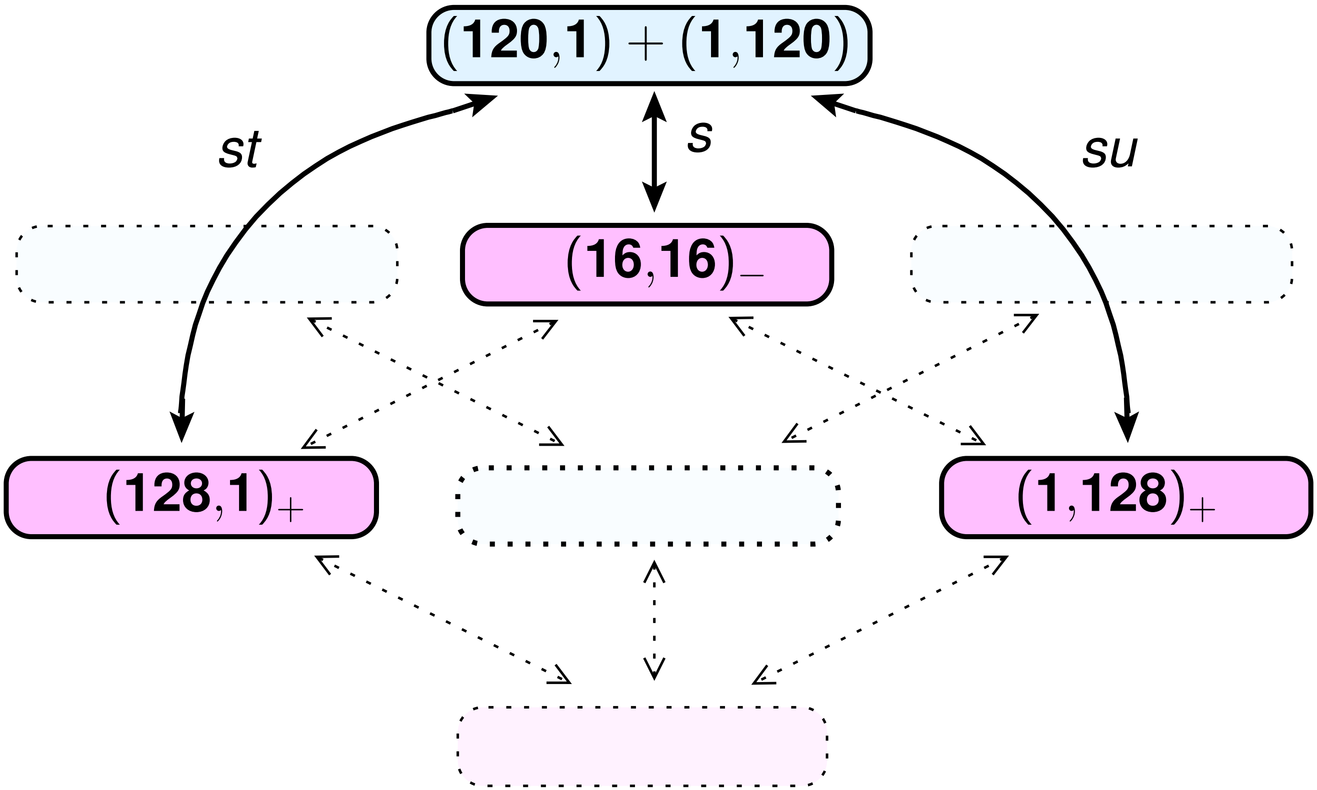
The SO(16)×SO(16) theory:



Possible similar induced transformations ???

Spin-structures as SUSY-like generators

The SO(16)×SO(16) theory:



Possible similar induced transformations ???

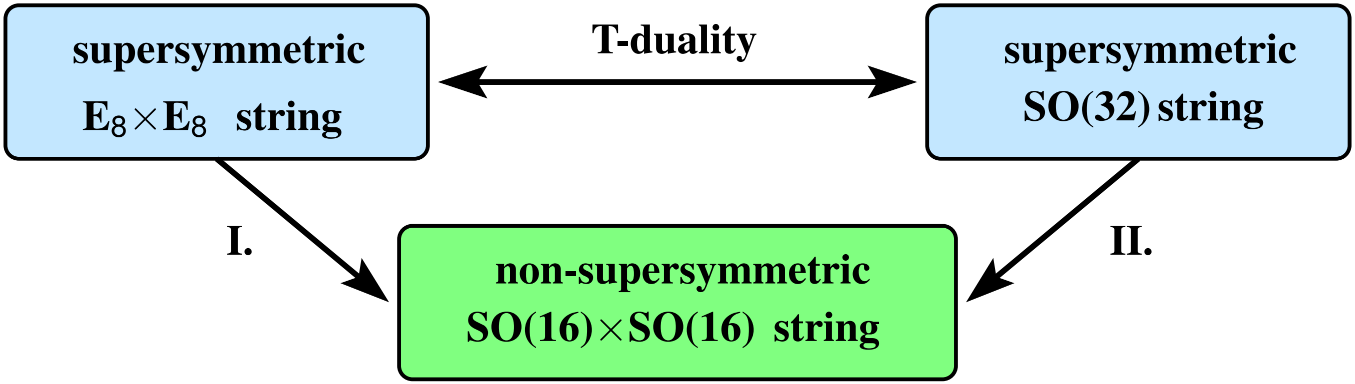
Fermionic SUSY-like transformations???

In the SO(16)×SO(16) theory this seems to suggest fermionic transformations, like: SGN,Parr'16

$$\delta_s A_M^{(\mathbf{120},\mathbf{1})} \quad \sim \quad \Psi_-^{(\mathbf{16},\mathbf{16})} \,, \qquad \delta_s \Psi_-^{(\mathbf{16},\mathbf{16})} \quad \sim \quad A_N^{(\mathbf{120},\mathbf{1})}$$

This requires that the susy/gauge parameters carry both space-time spinors as well as non-trivial gauge indices

The SO(16)×SO(16) string as an orbifold



The SO(16)×SO(16) theory can be obtained by: Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

- **I. SUSY breaking orbifolding of the $E_8 \times E_8$ string**
- **II. SUSY breaking orbifolding of the SO(32) string**

N=1 4D superfields for 10D super-Yang-Mills

The 10D super-Yang-Mills can be written as in terms of N=1 4D superfields Marcus,Sagnotti,Siegel'83, Arkani-Hamed,Gregoire,Wacker'01

4D superfield : Components		**Interpretation**
Vector : V **:**	$[\overline{D}_{\dot\alpha}, D_\alpha]V\| = \sigma^\mu_{\alpha\dot\alpha} A_\mu$	4D Minkowski gauge fields
	$\overline{D}^2 D_\alpha V\| = \lambda_\alpha$	4D gauginos
Chiral : Φ_i **:**	$\Phi_i\| = A_i$	6D internal gauge fields
	$D_\alpha \Phi_i\| = \psi_{i\alpha}$	N=4 gaugino partners

using complex coordinates $i = 1, 2, 3$ for the six internal directions

These superfields can be in the adjoint of $E_8 \times E_8$ or SO(32)

EFT description of the SUSY breaking twist

The supersymmetry breaking twist can be represented on N=1 4D superspace as

$$\theta \to -\theta \,, \qquad \bar{\theta} \to -\bar{\theta} \,, \qquad x \to x$$

and consequently on the superfields Blaszczyk,SGN,Loukas,Ruehle'15

$$V(\theta) \to V(-\theta) = Z\, V(\theta)\, Z \,, \qquad \Phi_i(\theta) \to \Phi_i(-\theta) = Z\, \Phi_i(\theta)\, Z$$

where Z unitary matrix that squares to the identity:

$$Z^2 = \mathbb{1} \,, \qquad Z^\dagger = Z^{-1} = Z$$

SUSY breaking twist invariant states

For example the supersymmetry breaking twist from SO(32) to SO(16)×SO(16) can be realized by

$$\Phi_i(\theta) \to \Phi_i(-\theta) = Z\,\Phi_i(\theta)\,Z \quad , \quad Z = \begin{pmatrix} -\mathbb{1}_{16} & 0 \\ 0 & \mathbb{1}_{16} \end{pmatrix}$$

The supersymmetry breaking twist invariant states from

$$\Phi_i(\theta) = A_i + \theta^\alpha\, \psi_{i\,\alpha} + \theta^2\, F_i = \begin{pmatrix} (\mathbf{120}, \mathbf{1}) & (\mathbf{16}, \mathbf{16}) \\ \text{-}(\mathbf{16}, \mathbf{16})^T & (\mathbf{1}, \mathbf{120}) \end{pmatrix}$$

are the untwisted SO(32) states of the SO(16)×SO(16) theory:

	Bosonic	**Fermionic**
States	10D gauge fields D-/F-fields	N=4 gauginos
Reprs	$(\mathbf{120},\mathbf{1}) + (\mathbf{1},\mathbf{120})$	$(\mathbf{16},\mathbf{16})$

Fermionic symmetries from super gauge transformations

We have a similar decomposition for the super gauge parameters

$$\Lambda(\theta) = \alpha + \theta^\alpha \rho_\alpha + \theta^2 f = \begin{pmatrix} (\mathbf{120}, \mathbf{1}) & (\mathbf{16}, \mathbf{16}) \\ \text{-}(\mathbf{16}, \mathbf{16})^T & (\mathbf{1}, \mathbf{120}) \end{pmatrix}$$

in the super gauge transformations

$$V \to e^{\overline{\Lambda}} V e^{\Lambda} , \qquad \Phi_i \to e^{-\Lambda} \big(\Phi_i + \partial_i\big) e^{\Lambda}$$

Hence, fermionic transformations like SGN,Parr'16

$$\psi_{i\,\alpha} \to \partial_i \rho_\alpha + [A_i, \rho_\alpha]$$

survive the supersymmetry breaking twist

Twisted superspace

The ~~SUSY~~-breaking twist can obviously generalized to any N=1 4D SUSY theory SGN,Parr'16

$$\theta \rightarrow -\theta \,, \qquad \bar{\theta} \rightarrow -\bar{\theta} \,, \qquad x \rightarrow x$$

and consequently on the superfields

$$V(\theta) \rightarrow V(-\theta) = Z\, V(\theta)\, Z \,, \qquad \Phi(\theta) \rightarrow \Phi(-\theta) = \mathcal{Z}\, \Phi(\theta)$$

where $Z^2 = \mathbb{1} \,, \qquad Z^\dagger = Z^{-1} = Z \,, \qquad \mathcal{Z} = \varrho(Z)$

Even if one starts with an anomaly-free spectrum, after the ~~SUSY~~-breaking twist the spectrum will in general be anomalous

Untwisted sectors of the SUSY breaking twists:

supersymmetric $E_8\times E_8$ string —I.→ **non-supersymmetric $SO(16)\times SO(16)$ string**

supersymmetric $E_8\times E_8$ string	non-supersymmetric $SO(16)\times SO(16)$ string
Graviton, B-field, Dilaton $E_8\times E_8$ Gauge fields	Graviton, B-field, Dilaton $SO(16)\times SO(16)$ Gauge fields
Gravitino, Dilatino $E_8\times E_8$ Gauginos	– $(\mathbf{128},\mathbf{1})_+ + (\mathbf{1},\mathbf{128})_+$

supersymmetric $SO(32)$ strings —II.→ **non-supersymmetric $SO(16)\times SO(16)$ strings**

supersymmetric $SO(32)$ strings	non-supersymmetric $SO(16)\times SO(16)$ strings
Graviton, B-field, Dilaton $SO(32)$ Gauge fields	Graviton, B-field, Dilaton $SO(16)\times SO(16)$ Gauge fields
Gravitino, Dilatino $SO(32)$ Gauginos	– $(\mathbf{16},\mathbf{16})_-$

All massless states of the $SO(16)\times SO(16)$ theory are untwisted states from either the $E_8\times E_8$ or $SO(32)$ theory

Quantum corrections in non-supersymmetric theories

Wess-Zumino model with SUSY breaking twist

To systematically study quantum effects in an EFT language, we consider the simplest Wess-Zumino model

$$S = \int \mathrm{d}^4x\mathrm{d}^4\theta\, \overline{\Phi}\Phi + \int \mathrm{d}^4x\mathrm{d}^2\theta\, W(\Phi) + \text{h.c.}\,,$$

with

$$W(\Phi) = t\,\Phi_+ + \tfrac{1}{2}\,m\,(\Phi_+^2 + \Phi_-^2) + \tfrac{1}{2}\,\lambda\,\Phi_+^3 + \tfrac{1}{2}\,\lambda\,\Phi_+\,\Phi_-^2$$

The supersymmetry breaking twist

$$\Phi_\pm(\theta) \to \Phi_\pm(-\theta) = \pm\,\Phi_\pm(\theta)$$

keeps:

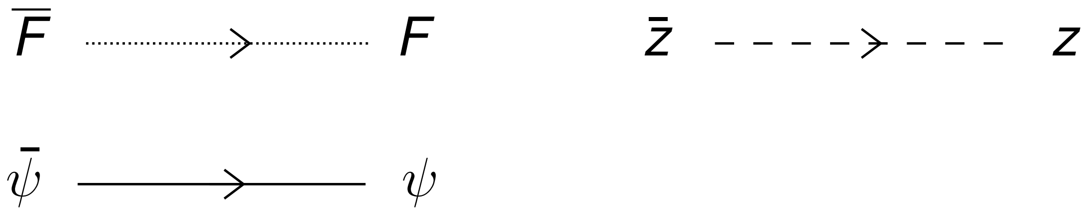
$Z = +1$	Φ_+	bosons : z, F
$Z = -1$	Φ_-	fermion : ψ_α

using the usual chiral superspace expansion

$$\Phi = z + \theta^\alpha\,\psi_\alpha + \theta^2\,F$$

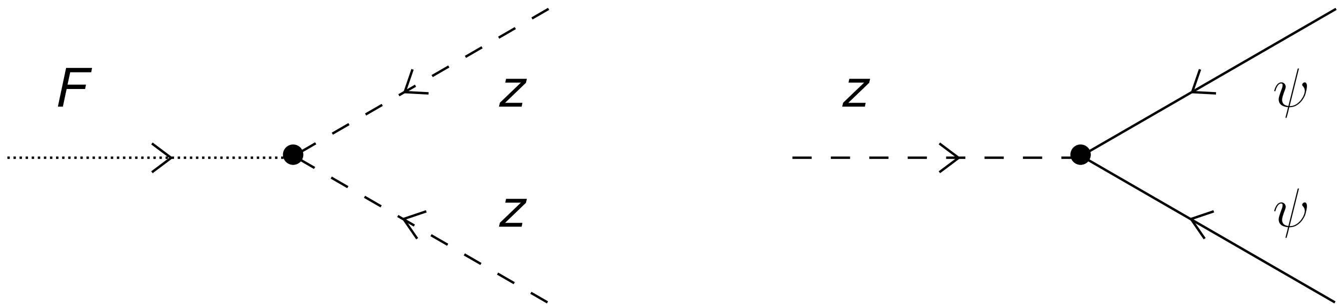
Component Feyman rules

Propagators:



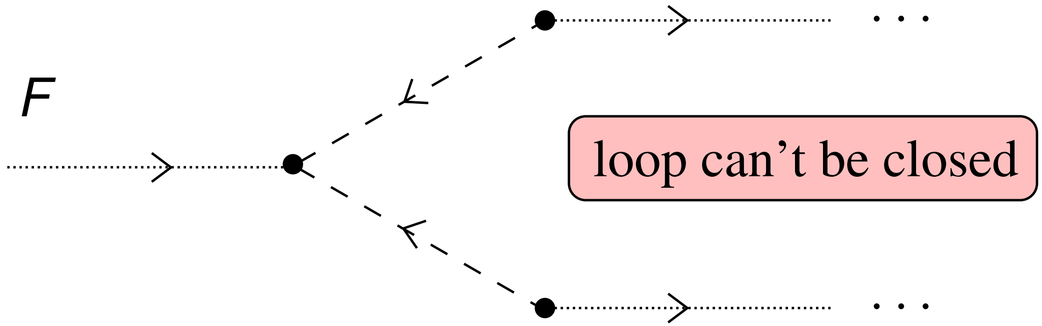
2-point (mass) vertices:

3-point vertices:



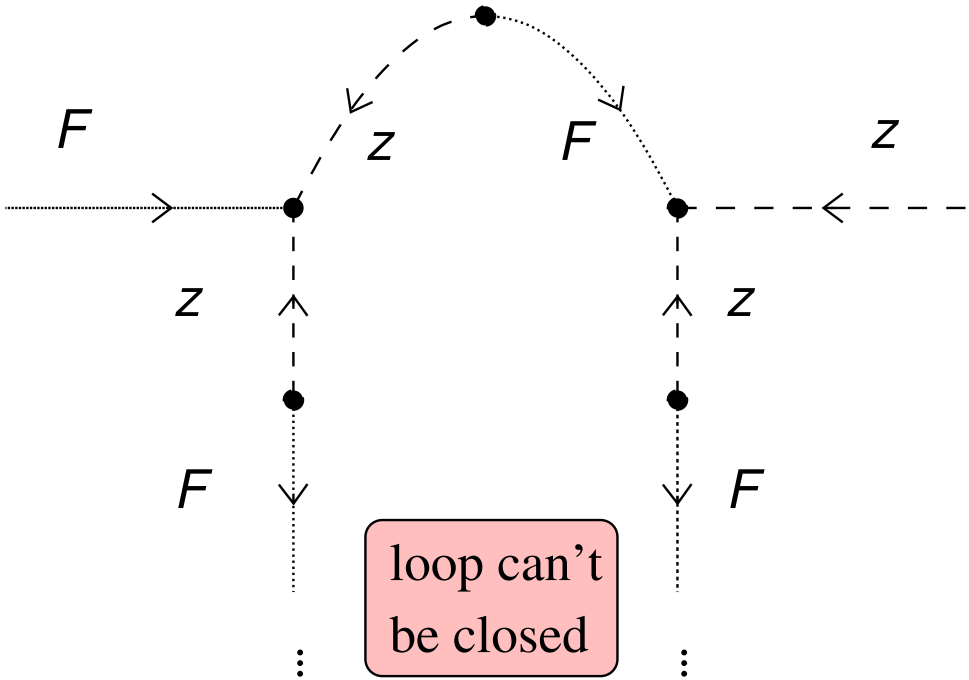
Non-renormalizations at one loop

No one-loop tadpole graph for F:



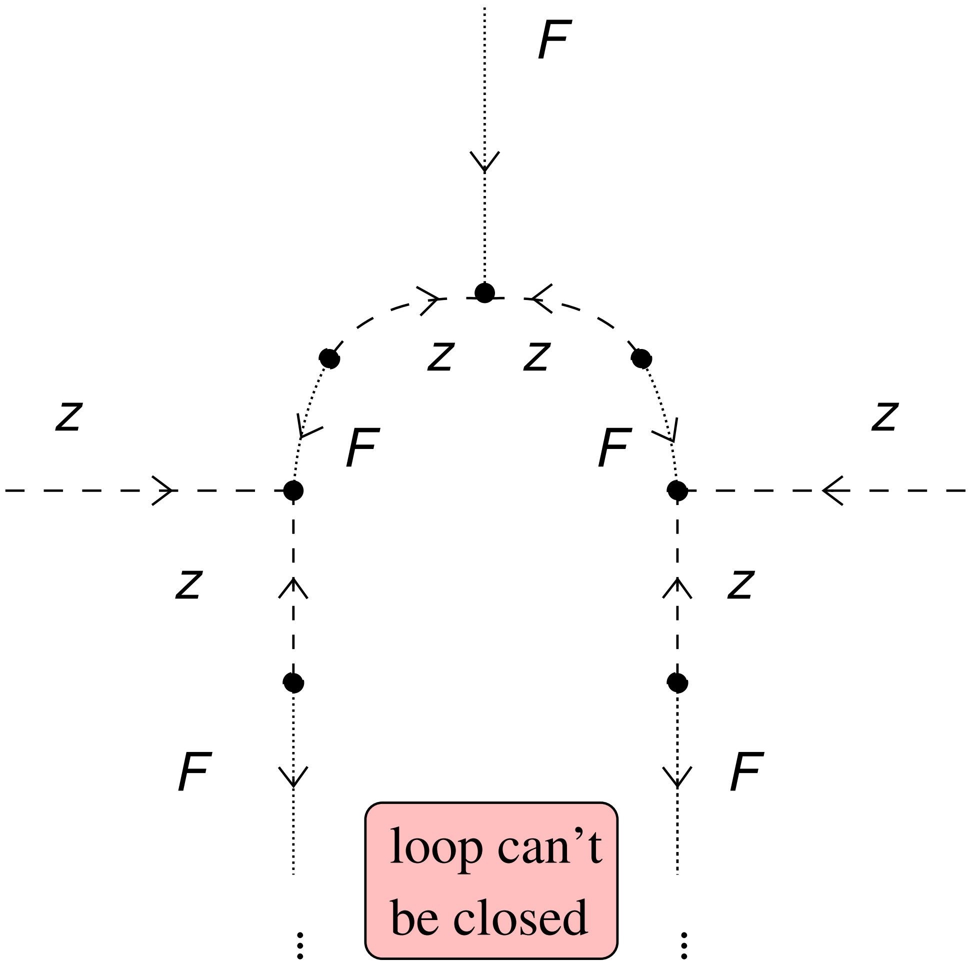
Non-renormalizations at one loop

No one-loop mass renormalization Fz:



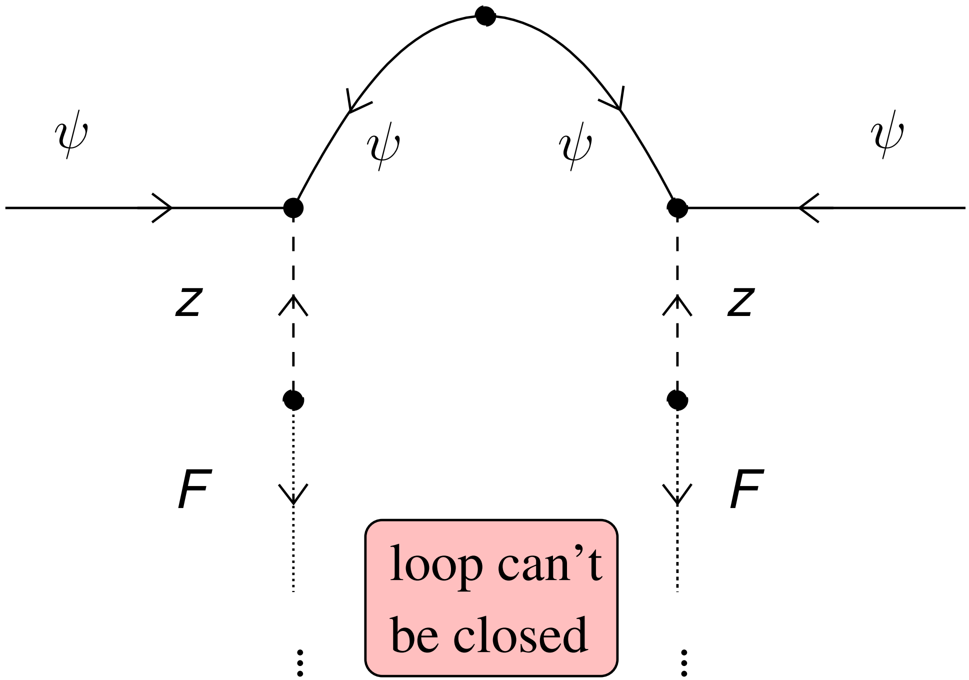
Non-renormalizations at one loop

No one-loop renormalization of the Fzz coupling:



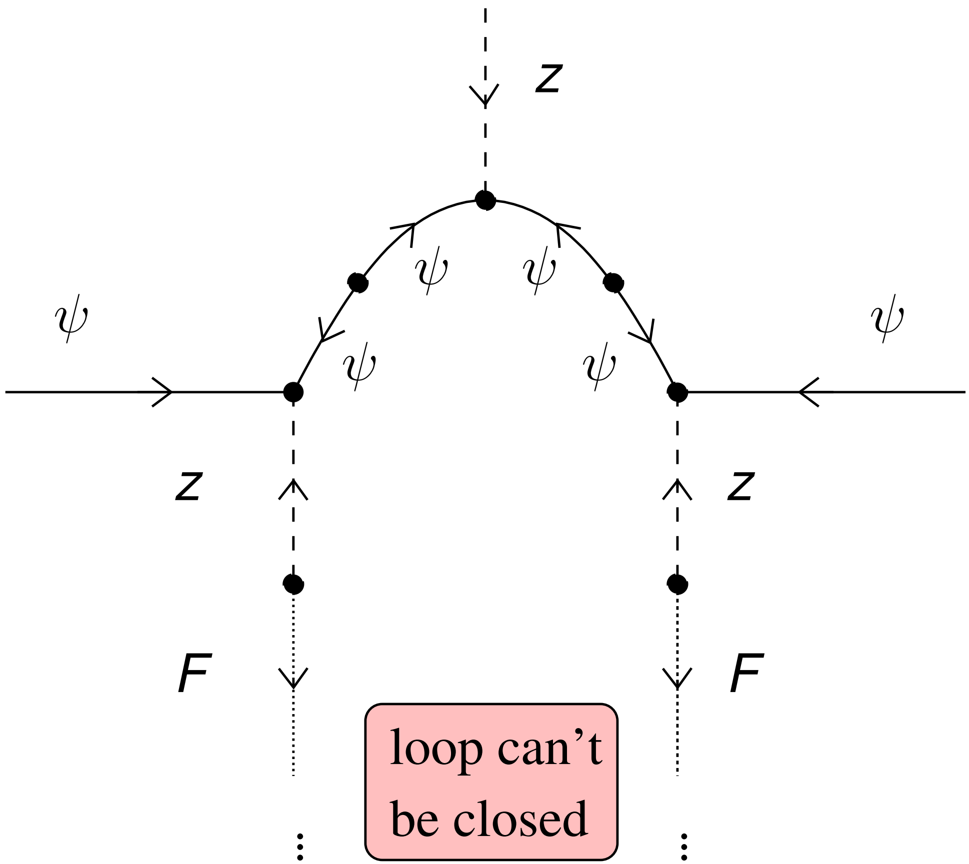
Non-renormalizations at one loop

No one-loop mass renormalization ψ:



Non-renormalizations at one loop

No one-loop renormalization of the $z\psi\psi$ Yukawa coupling:



Nonrenormalization at one loop

Conclusion:

The interactions derived from the superpotential

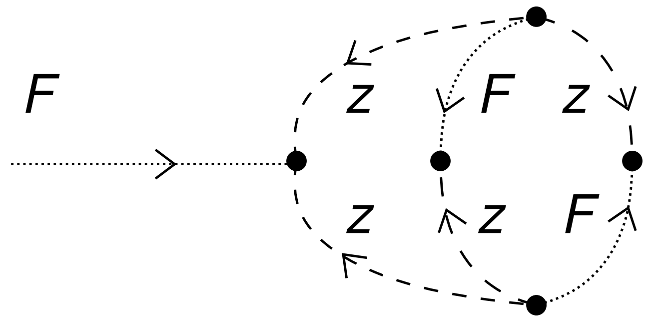
$$\int \mathrm{d}^2\theta\, W(\Phi) = t\, F + m\, Fz + \tfrac{1}{2}\,\lambda\, Fz^2 + \tfrac{1}{2}\,(m + \lambda\, z)\, \psi^2$$

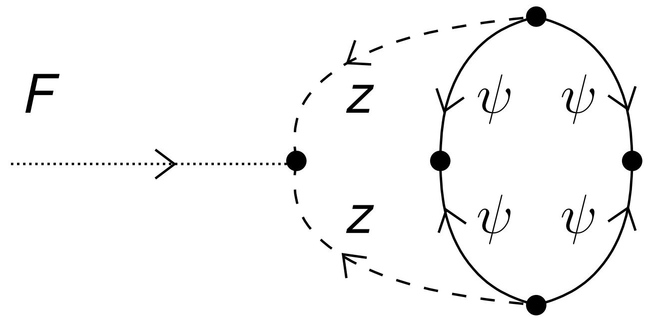
do not renormalize at the one-loop level

SGN,Parr'16

The superpotential renormalizes beyond 1 loop

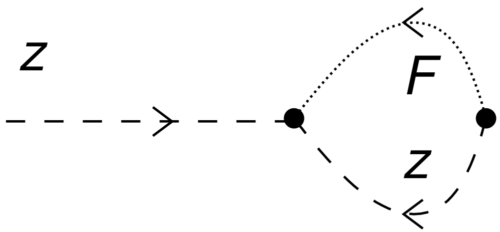
The first non-trivial diagrams arise at the two-loop level:

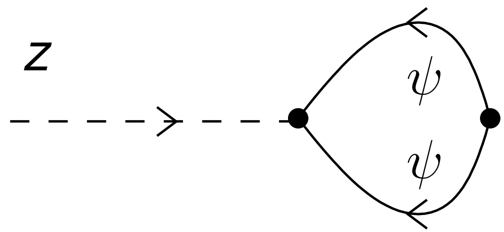




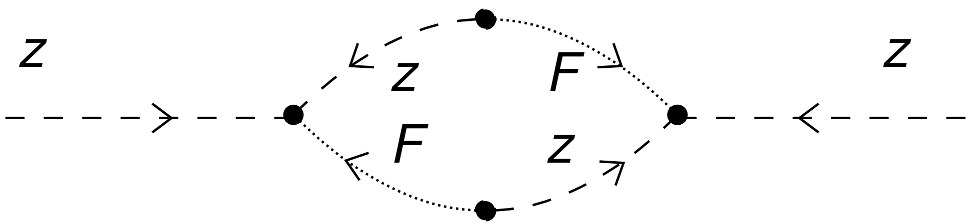
One loop renormalizations

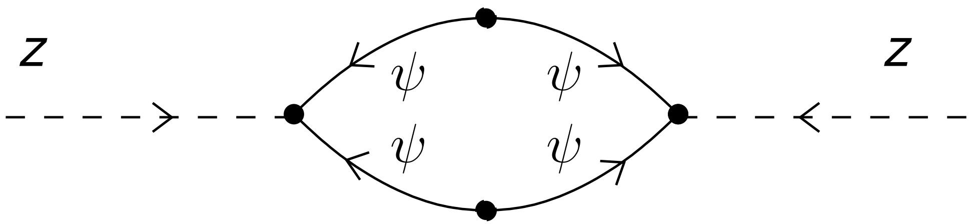
One-loop tadpole graphs for z:





One-loop mass renormalization graphs for z:





One loop renormalizations

These diagrams generate “soft” terms

$$S_{\text{“soft”}} = \int \mathrm{d}^4x \mathrm{d}^2\theta\ \theta^2\, \widetilde{W}(\Phi)\ , \quad \widetilde{W}(\Phi) = \widetilde{t}\,\Phi + \tfrac{1}{2}\,\widetilde{m}\,\Phi^2 + \tfrac{1}{3!}\,\widetilde{\lambda}\,\Phi^3$$

$$= \int \mathrm{d}^4x\ \widetilde{t}\,z + \tfrac{1}{2}\,\widetilde{m}\,z^2 + \tfrac{1}{3!}\,\widetilde{\lambda}\,z^3$$

at one loop SGN,Parr’16

These interactions parameterized in terms of the spurion superfield θ^2

The tadpole is not “soft” but generically quadratically divergent

SUSY-twisted supergraphs

To define supergraphs one needs functional derivative w.r.t. the sources of the superfields in the theory.

Since the superfields now have SUSY-twisted boundary conditions

$$\Phi(-\theta) = \mathcal{Z}\,\Phi(\theta)$$

we need SUSY-compatible delta functions SGN,Parr'16

$$\frac{\delta J_1{}^a}{\delta J_2{}^b} = -\tfrac{1}{4}\overline{D}_2^2\,\big(\tilde{\delta}_{21}\big)^a{}_b$$

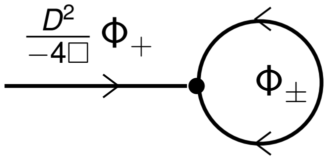
with

$$\big(\tilde{\delta}_{21}\big)^a{}_b = \tfrac{1}{2}\,\delta^4(x_1 - x_2)\,\Big\{(\theta_2 - \theta_1)^4\delta^a{}_b + (\theta_2 + \theta_1)^4\,\mathcal{Z}^a{}_b\Big\}$$

Tadpole for z

Consider the tadpole supergraph:

$T \quad =$



$$= \quad \frac{1}{4}\,\lambda_\pm \int (\mathrm{d}^4 x\,\mathrm{d}^4\theta)_{12} \left[\frac{D^2}{-4\Box}\Phi_+\right]_1 \tilde{\delta}_{12} \left[\frac{\overline{m}_\pm}{\Box - |m_\pm|^2}\,\frac{\overline{D}^2}{-4}\right]_2 \tilde{\delta}_{12}$$

Inserting the twist compatible delta functions gives two types of contributions:

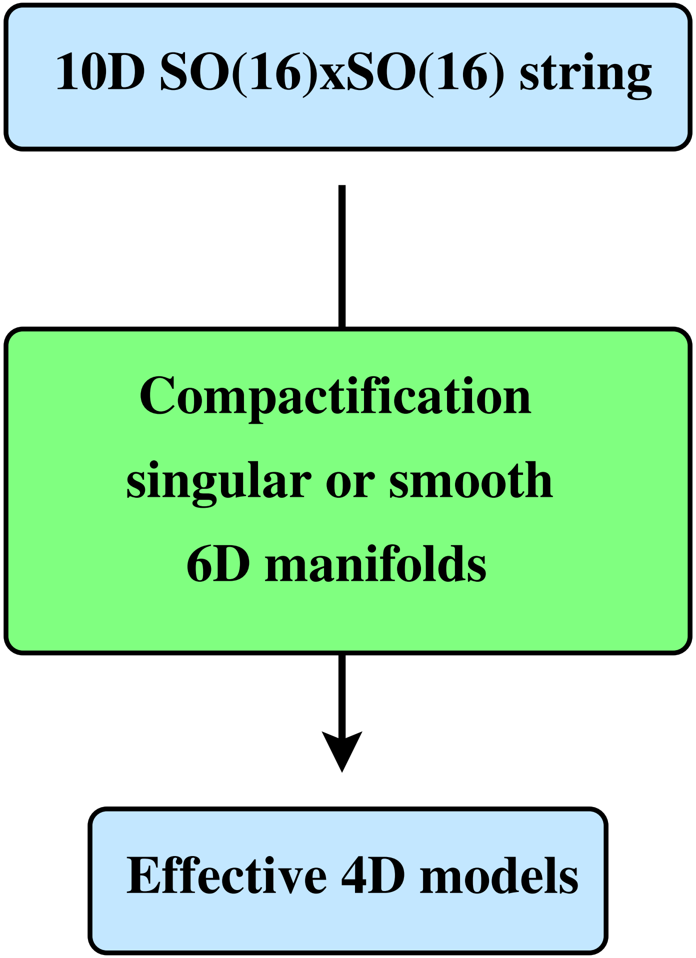
- one that vanishes (as in the SUSY case)
- a spurion θ^2 insertion:

$$T_{\text{div}} \;=\; \mp\, 2\,\lambda_\pm \int \frac{\mathrm{d}^4 q}{(2\pi)^4}\,\frac{\overline{m}_\pm}{q^2 + |m_\pm|^2} \int \mathrm{d}^4 x \mathrm{d}^4\theta\;\theta^2\,\frac{D^2}{-4\Box}\Phi_+$$

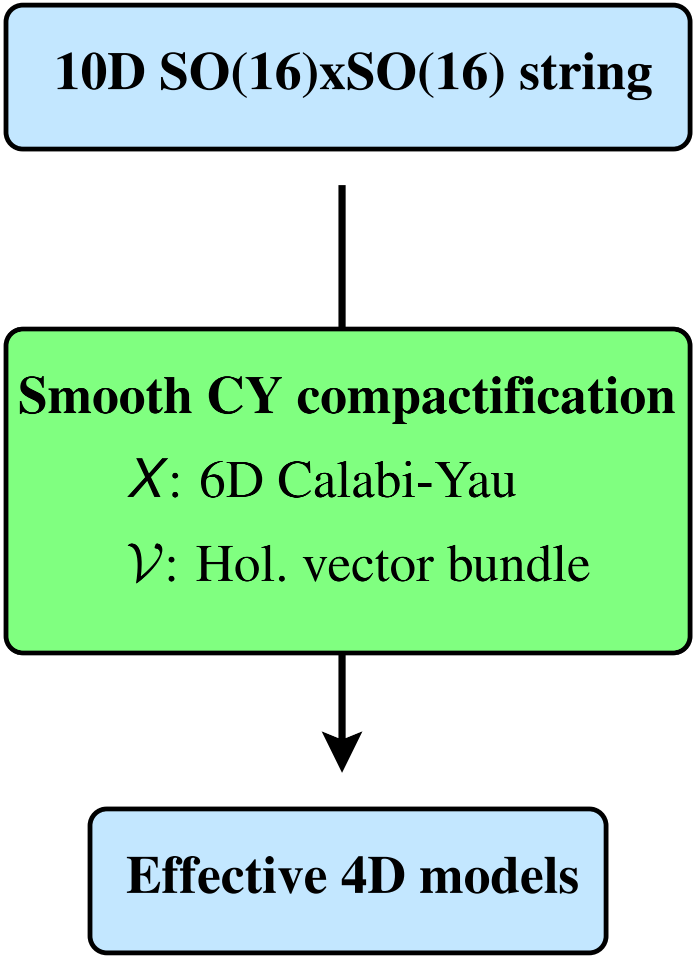
which is indeed a tadpole for z because

$$\int \mathrm{d}^4\theta\;\theta^2\,\frac{D^2}{-4\Box}\Phi_+ = z$$

Non-supersymmetric string compactifications



The SO(16)×SO(16) string on Calabi-Yaus



CY backgrounds for SO(16)×SO(16) string

Why consider CY backgrounds for non-SUSY strings?

- **Target space: Avoid tachyons**

  Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

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

  The Laplace operator $\Delta \sim (i\not{D})^2$ is related to the square of the Dirac operator $i\not{D}$, hence its spectrum is non-negative

- **We can recycle many computational techniques**

Line bundles on smooth Calabi-Yaus

A crude topological characterization of a smooth Calabi-Yau is given by

- the Hodge numbers h_{11} and h_{21}
- the second Chern class $c_2(X)$
- the divisor classes D_i
- their intersection numbers $\kappa_{ijk} = \int_X D_i D_j D_k$

A line bundle background can be defined as

$$\frac{\mathcal{F}_2}{2\pi} = V_i^I \, D_i \, H_I$$

where H_I are the Cartan generators of SO(16)×SO(16)

Line bundles on smooth Calabi-Yaus

Such line bundle backgrounds have to satisfy various consistency conditions:

- **Flux quantization:**

$$\int_C \frac{\mathcal{F}_2}{2\pi} \in \mathbb{Z} \quad \Leftrightarrow \quad V_i \in \mathbf{R}_8 \times \mathbf{R}_8$$

- **Bianchi identities:**

$$\int_D (\mathrm{tr}\mathcal{F}_2^2 - \mathrm{tr}\mathcal{F}_2^2) = 0 \quad \Leftrightarrow \quad \kappa_{ijk}\, V_i \cdot V_j - 2\, c_{2i} = 0$$

- **Tree-level DUY equations:**

$$\int J^2 \frac{\mathcal{F}_2}{2\pi} = 0 \quad \Leftrightarrow \quad \mathrm{Vol}(D_i) \cdot V_i = 0$$

Why does these define good backgrounds for the non-SUSY string?

The effective action of the non-SUSY heterotic SO(16)$\times$SO(16) is the same as that of the SUSY $E_8\times E_8$ or SO(32) heterotic strings:
Blazczyk,SGN,Loukas,Ruehle'15

Their 10D bosonic actions are fixed by general coordinate and gauge invariance only!

The one-loop beta functions are identical as the worldsheet field content are all identical.

However, beyond leading order in g_s there will be modifications:

- cosmological constant
- dilaton-tadpole
- loop corrected DUY

SM-like model scans on smooth Calabi-Yaus

Inequivalent SU(5) models for SO(16)×SO(16) theory on smooth CYs									
Geometry		GUT-	Chiral exact			SM-	Chiral exact		
h_{11}	Name (CICY #)	like	Fermi	Scalar	Both	like	Fermi	Scalar	Both
4	Tetra-quartic (7862)	209,743	281	263	1	1,575,098	2,370	2,000	15
4	7491, 7522	1,873	0	1	0	14,651	0	11	0
5	7447, 7487	28,209	901	46	5	149,143	5,154	377	52
5	6770	65,888	173	85	0	437,327	914	707	0
5	6715, 6788, 6836, 6927	120	7	0	0	518	89	0	0
5	6732, 6802, 6834, 6896	460	33	0	0	3,119	275	0	0
5	6225	72	0	0	0	483	0	0	0
6	5302	355	22	0	0	1093	66	0	0
19	Schoen	456,594	5,169	2,745	30	3,002,353	37,276	21,955	237

SGN,Loukas,Ruehle'15

(CICY classifications Candelas,Dale,Lutken,Schimmrigk'88, Braun'10)

(0,2) aspects of non-SUSY heterotic strings

$E_8 \times E_8$ and $SO(16) \times SO(16)$ Partition functions

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

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

$$\mathbf{Z}_{SO(16)^2} = \sum_{\text{spin}} T \cdot \mathbf{Z}_8^x(\tau,\bar\tau) \cdot \widehat{\mathbf{Z}}_4 \left[{s \atop s'}\right](\tau) \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{t \atop t'}\right](\tau)} \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{u \atop u'}\right](\tau)}$$

with torsion phases Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

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

(0,2) aspects of non-SUSY heterotic strings

The SUSY $E_8 \times E_8$ and non-SUSY $SO(16) \times SO(16)$ strings

- the same worldsheet fields
- with the same boundary conditions (corresponding to the different spin-structures)
- and consequently identical partition functions in each of the spin-structure sectors
- except that they are combined in a different way because of the torsion phases

(0,2) aspects of non-SUSY heterotic strings

This seems to suggest that also worldsheet theories with enhanced symmetry, like (0,2) or (2,2) models and GLSMs, should still have very special properties

Moreover, various localization techniques to compute partition functions in the SUSY sectors on the worldsheet should still apply

- Which ones can simply be recycled and which have ones have to be recalculated?
- What would they compute in the non-SUSY context?

How do the one-loop in g_s induced vacuum energy and dilaton tadpole effects the (0,2) or (2,2) constructions?

Summary / Outlook

We have seen that studying non-supersymmetric models in string theory is interesting both theoretically and phenomenologically

But there are still many open difficult and fundamental questions here to be addressed...

Thank you!