Non-supersymmetric heterotic model building

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EPS HEP2015, Vienna, July 25, 2015
This talk is based on collaborations with:

Michael Blaszczyk

Orestis Loukas

Ramos-Sanchez

Fabian Ruehle
and publications:

- JHEP 1410 (2014) 119 [arXiv:1407.6362]
- DISCRETE’14 proceedings [arXiv:1502.03604]
- arXiv:1507.06147
- arXiv:1507.soon!
Main motivation: Where is Supersymmetry?

**ATLAS SUSY Searches** - 95% CL Lower Limits

Status: Feb 2015

**ATLAS** Preliminary

\[ \sqrt{s} = 7, 8 \text{ TeV} \]

- **Motivation**
  - Main motivation: Where is Supersymmetry?

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**3rd gen. squarks, gluinos**

- **Direct production**
  - \( \tilde{g}\)\(\tilde{g}\), \(\tilde{b}_L\)\(\tilde{t}_L\)
  - \(\tilde{b}_L\)\(\tilde{b}_L\), \(\tilde{t}_L\)\(\tilde{t}_L\), \(\tilde{q}\)\(\tilde{q}\)

- **EW direct**
  - \(\tilde{t}_R\)\(\tilde{t}_R\), \(\tilde{b}_R\)\(\tilde{b}_R\), \(\tilde{t}_R\)\(\tilde{t}_R\)

- **Long-lived particles**
  - \(\tilde{\chi}_{1}^{0}\) prod., long-lived \(\tilde{\chi}_{1}^{0}\)
  - Stable, stopped \(\tilde{g}\) R-hadron
  - Stable \(\tilde{g}\) R-hadron

- **RPV**
  - LFV \(p\bar{p}\rightarrow\nu\bar{\nu}+X\)\(\nu\rightarrow\nu+\mu\)
  - Bilinear RPV CMSSM

- **Other**
  - Scalar charm, \(\tilde{c}\rightarrow\tilde{c}\)

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**Models**

- **MSUGRA/CMSSM**
- **GMSB (NLSP)**
- **GGM (higgsino-bino NLSP)**
- **Gravitino LSP**
- **Non-SUSY string models**

**Mass limits**

- **Reference**
- **\(m_{\tilde{q}}\)**
- **\(m_{\tilde{\chi}^0_1}\)**
- **\(m_{\tilde{g}}\)**
- **\(m_{\tilde{t}}\)**
- **\(m_{\tilde{b}}\)**

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**Table**

- **Model**
- **\(e, \mu, \tau, \gamma, J_{\text{ets}}\)**
- **\(E_{\text{miss}}^{T}\)**
- **Mass limit [TeV]**
- **Reference**

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**Graph**

- **\(\sqrt{s} = 7, 8 \text{ TeV} \)**
- **\(\sqrt{s} = 8 \text{ TeV} \)**
- **\(\sqrt{s} = 8 \text{ TeV} \)**

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**Non-SUSY string models**

**EPS, Vienna, July 25, 2015**

**3 / 23**
Main motivating questions:

- So far no supersymmetry found, what if this stays this way?
- Can string theory exist without supersymmetry?
- What is the supersymmetry breaking mechanism in string theory?
Major issues without supersymmetry

- Hierarchy problem
- Cosmological constant problem
- Dilaton tadpole
- Tachyons
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
Motivation

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

- Calabi-Yau compactifications of non-supersymmetric heterotic string theory
  Blaszczyk, SGN, Loukas, Ruehle’15
Overview of this talk

1. Motivation
2. The non-supersymmetric heterotic string
3. Non-supersymmetric five branes?
4. Smooth compactifications
5. Orbifold compactifications
Well-known 10D string theories

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

However, it disregards various non-supersymmetric strings...
10D tachyon-free (non-)supersymmetric strings

- **Motivation**
  - 10D tachyon-free (non-)supersymmetric strings
  - **N = 0**
    - Heterotic
    - SO(16) x SO(16)
  - **N = 1**
    - Heterotic E_8 x E_8
  - **N = 2**
    - 11D SUGRA

- **Types**
  - Type IIA
  - Type IIB
  - Type 0’ USp(32)
  - Type 0’ U(32)
  - Type I SO(32)

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10D tachyon-free (non-)supersymmetric strings

Motivation

11D SUGRA

- Type 0’ USp(32)
- Heterotic SO(32) × SO(16)
- Type I SO(32)
- Type IIA
- Type IIB

N = 0
- Heterotic
- N = 1
- Heterotic E_8 × E_8
- N = 2

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Non-SUSY string models

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The non-supersymmetric heterotic string

The low-energy spectrum of the non-supersymmetric SO(16) × SO(16) heterotic string reads: Dixon, Harvey’86, Alvarez-Gaume, Ginsparg, Moore, Vafa’86

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

This theory is also modular invariant, anomaly- and tachyon-free but obviously not supersymmetric.
Constructions of the $SO(16) \times SO(16)$ string

The $SO(16) \times SO(16)$ 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
Untwisted sectors of the SUSY breaking twists:

I. supersymmetric \( E_8 \times E_8 \) string

Graviton, B-field, Dilaton
\( E_8 \times E_8 \) Gauge fields
Gravitino, Dilatino
\( E_8 \times E_8 \) Gauginos

non-supersymmetric \( SO(16) \times SO(16) \) string

Graviton, B-field, Dilaton
\( SO(16) \times SO(16) \) Gauge fields

\( (128, 1)_+ + (1, 128)_+ \)

II. supersymmetric \( SO(32) \) strings

Graviton, B-field, Dilaton
\( SO(32) \) Gauge fields
Gravitino, Dilatino
\( SO(32) \) Gauginos

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

Graviton, B-field, Dilaton
\( SO(16) \times SO(16) \) Gauge fields

\( (16, 16)_- \)

All states of the \( SO(16) \times SO(16) \) theory can be understood as untwisted states of either the \( E_8 \times E_8 \) or \( SO(32) \) theory.
Non-supersymmetric five branes?

**Five branes for the SO(16) × SO(16) theory**

Recall: All SO(16) × SO(16) states can be understood as untwisted SUSY-twist sectors of the $E_8 \times E_8$ or SO(32) theory.
When one does K3 compactifications, that violate the Bianchi identity, one has to introduce NS5-branes...
Five branes for both the $E_8 \times E_8$ and $SO(32)$ are known; by the SUSY breaking twist we can infer the $SO(16) \times SO(16)$-branes.
Five branes for both the $E_8 \times E_8$ and $SO(32)$ are known; by the SUSY breaking twist we can infer the $SO(16) \times SO(16)$-branes
Non-supersymmetric five branes?

Five branes for the SO(16) × SO(16) theory

This analysis seems to suggest that there are two type of NS5-branes in the SO(16) × SO(16) theory

But only with at most a single combination of one $E_8 \times E_8$- and one SO(32)-type NS5-brane full anomaly cancellation and factorization seems to work
Compactifications of the $\text{SO}(16) \times \text{SO}(16)$ string

10D $\text{SO}(16) \times \text{SO}(16)$ string

\[ \text{Smooth CY compactification} \]

\[ X: 6D \text{ Calabi-Yau} \]

\[ V: \text{ Hol. vector bundle} \]

\[ \text{SM–like models} \]
Why consider CY backgrounds for non-SUSY strings?

- **Target space: Avoid tachyons**
  Blaszczyk, SGN, Loukas, Ramos-Sanchez’14

- **Worldsheet: U(1)$_R$ symmetry and (2,0) SUSY**
  Hull, Witten’85

- **We can recycle many computational techniques**
**SM-like model scans on smooth Calabi-Yaus**

| $h_{11}$ | Geometry (Name / CICY #) | Upstairs picture | Downstairs picture |
|----------|--------------------------|------------------|-------------------|
|          |                          | GUT-like | Chiral exact | SM-like | Chiral exact |
| 4        | Tetra-Quadric (7862)     | 63,768   | 2           | 235,232 | 9           |
| 4        | 7491, 7522               | 1        | 0           | 7        | 0           |
| 5        | 7447, 7487               | 10,553   | 3           | 56,474   | 25          |
| 5        | 6770                     | 204      | 0           | 1,279    | 0           |
| 5        | 6715, 6788, 6836, 6927   | 68       | 0           | 143      | 0           |
| 5        | 6732, 6802, 6834, 6896   | 15       | 0           | 86       | 0           |
| 5        | 6225                     | 0        | 0           | 0        | 0           |
| 6        | 5302                     | 173      | 0           | 431      | 0           |
| 19       | Schoen                   | 305,661  | 0           | 2,207,125| 0           |

SGN,Loukas,Ruehle’15

(CICY classifications Candelas,Dale,Lutken,Schimmrigk’88, Braun’10)
Orbifold compactifications

$\text{SO}(16) \times \text{SO}(16)$ orbifolds

- 10D $\text{SO}(16) \times \text{SO}(16)$ string

  - 6D orbifold compactification
    - $\nu$: $\mathbb{Z}_N$ orbifold twist
    - $\mathcal{V}$: $\mathbb{Z}_N$ gauge shift

  - SM–like models
**Orbifold compactifications**

**SO(16) × SO(16) orbifolds**

- **10D supersymmetric**
  - $E_8 \times E_8$ string

- **10D non-supersymmetric**
  - $SO(16) \times SO(16)$ string

- **4D supersymmetric**
  - $E_8 \times E_8$ string

- **4D non-supersymmetric**
  - $SO(16) \times SO(16)$ string

SUSY breaking $\mathbb{Z}_2$ twist: $v_0 = (0, 1^3)$, $V_0 = (1, 0^7)(-1, 0^7)$
Orbifold compactifications

SO(16) \times SO(16) orbifolds

10D supersymmetric
E_8 \times E_8 string

4D supersymmetric
E_8 \times E_8 string

10D non-supersymmetric
SO(16) \times SO(16) string

4D non-supersymmetric
SO(16) \times SO(16) string

Orbifold
(v, V)

SUSY
(v_0, V_0)

SUSY orbifold
(v_0, V_0), (v, V)

Orbifold
(v, V)

But then one can do a \mathbb{Z}_2 \times \mathbb{Z}_N orbifold directly...
Orbifold compactifications

SO(16) \times SO(16) orbifolds

10D supersymmetric
E_8 \times E_8 string

\text{SUSY orbifold}
(n_0, V_0), (n, V)

4D non-supersymmetric
SO(16) \times SO(16) string

implemented in the "Orbifolder"

Nilles, Ramos-Sanchez, Vaudrevange, Wingerter'11
# Twisted tachyons

Tachyons are possible in some twisted sectors of many orbifolds:

Blaszczyk,SGN,Loukas,Ramos-Sanchez’14

| Orbifold   | Twist  | Tachyons | Orbifold           | Twists                          | Tachyons |
|------------|--------|----------|--------------------|---------------------------------|----------|
| $T^6/\mathbb{Z}_3$ | $\frac{1}{3}(1,1,-2)$ | forbidden | $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ | $\frac{1}{2}(1,-1,0)$; $\frac{1}{2}(0,1,-1)$ | forbidden |
| $T^6/\mathbb{Z}_4$ | $\frac{1}{4}(1,1,-2)$ | forbidden | $T^6/\mathbb{Z}_2 \times \mathbb{Z}_4$ | $\frac{1}{2}(1,-1,0)$; $\frac{1}{4}(0,1,-1)$ | possible |
| $T^6/\mathbb{Z}_6$ | $\frac{1}{6}(1,1,-2)$ | possible | $T^6/\mathbb{Z}_2 \times \mathbb{Z}_6$ | $\frac{1}{2}(1,-1,0)$; $\frac{1}{6}(1,1,-2)$ | possible |
| $T^6/\mathbb{Z}_6$ | $\frac{1}{6}(1,2,-3)$ | possible | $T^6/\mathbb{Z}_2 \times \mathbb{Z}_6$ | $\frac{1}{2}(1,-1,0)$; $\frac{1}{6}(0,1,-1)$ | 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 |
| $T^6/\mathbb{Z}_8$ | $\frac{1}{8}(1,2,-3)$ | possible | $T^6/\mathbb{Z}_3 \times \mathbb{Z}_6$ | $\frac{1}{3}(1,-1,0)$; $\frac{1}{6}(0,1,-1)$ | possible |
| $T^6/\mathbb{Z}_8$ | $\frac{1}{8}(1,3,-4)$ | possible | $T^6/\mathbb{Z}_4 \times \mathbb{Z}_4$ | $\frac{1}{4}(1,-1,0)$; $\frac{1}{4}(0,1,-1)$ | possible |
| $T^6/\mathbb{Z}_{12}$ | $\frac{1}{12}(1,4,-5)$ | possible | $T^6/\mathbb{Z}_6 \times \mathbb{Z}_6$ | $\frac{1}{6}(1,-1,0)$; $\frac{1}{6}(0,1,-1)$ | possible |

Comments:

- when tachyons are possible, they do not necessarily appear
- and tachyons are lifted in full blow-up...
## SM-like models scans on CY orbifolds

| Orbifold twist | #(geom) | Inequivalent scanned models | Tachyon-free percentage | SM-like tachyon-free models total | one-Higgs | two-Higgs |
|----------------|---------|-----------------------------|-------------------------|-----------------------------------|-----------|-----------|
| $Z_3$          | (1)     | 74,958                      | 100%                    | 128                               | 0         | 0         |
| $Z_4$          | (3)     | 1,100,336                   | 100%                    | 12                                | 0         | 0         |
| $Z_{6-I}$      | (2)     | 148,950                     | 55%                     | 59                                | 18        | 0         |
| $Z_{6-II}$     | (4)     | 15,036,790                  | 57%                     | 109                               | 0         | 1         |
| $Z_{8-I}$      | (3)     | 2,751,085                   | 51%                     | 24                                | 0         | 0         |
| $Z_{8-II}$     | (2)     | 4,397,555                   | 71%                     | 187                               | 1         | 1         |
| $Z_2 \times Z_2$ | (12)   | 9,546,081                   | 100%                    | 1,562                             | 0         | 5         |
| $Z_2 \times Z_4$ | (10)   | 17,054,154                  | 67%                     | 7,958                             | 0         | 89        |
| $Z_3 \times Z_3$ | (5)    | 11,411,739                  | 52%                     | 284                               | 0         | 1         |
| $Z_4 \times Z_4$ | (5)    | 15,361,570                  | 64%                     | 2,460                             | 0         | 6         |

Blaszczyk, SGN, Loukas, Ramos-Sanchez’14

### On orbifolds we can construct single Higgs-doublet models, like the SM (not MSSM)!
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!