Challenges for particle physics from strings

Michael Ratz

XVI Mexican Workshop on Particles and Fields
Puerto Vallarta, October 27, 2017

Based on collaborations with:
Physicists have been playing with strings for quite some time.
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String theories are perturbative limits of some mysterious theory

- Type I
- Type IIA
- Type IIB
- Heterotic E
- Heterotic O
- 11D SUGRA

String theory is believed to provide us with a consistent description of quantum gravity. Ultimately, it is hoped that string/M–theory provides us with a theory of everything.
String model building

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- Superstring theory requires 10 space–time dimensions
- 6 dimensions need to be compact
String compactifications

Violin: needs to be constructed in such a way that the oscillating strings produce the right sounds
String compactifications

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String compactification: twist the string in such a way that the excitations carry the quantum numbers of the standard model particles
Many popular attempts to connect strings with observation:

- heterotic orbifolds
- intersecting $D$–branes
- Calabi–Yau compactifications
- F–theory
- ...
From strings to the real world?

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Only the first two are true string models
(but the others are believed to relate to string compactifications)
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**main theme of the rest of this talk:**
orbifold compactifications of the heterotic string
Introduction

From strings to the real world?

Where do we stand?

Free fermionic construction: $10^7$ standard–like models (all different???)

e.g. Faraggi, Rizos & Sonmez (2017)
Free fermionic construction: $10^7$ standard–like models

F–theory

“However, despite the remarkable progress in F–theory model building in recent years, a number of important conceptual and phenomenological questions still remain open. In fact, to the best of our knowledge, at present there is no fully satisfactory F–theory GUT model, which would have to account for symmetry breaking to the standard model gauge group, the matter content of the (supersymmetric) standard model, doublet–triplet splitting, sufficiently suppressed proton decay, supersymmetry breaking and semi–realistic quark and lepton mass matrices.”
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- F–theory 😞

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- Heterotic mini–landscape search: $O(10^5)$ standard–like models
  
  Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange & Wingerter (2007a,c)
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- Complete classification of heterotic orbifold geometries
Fischer, M.R., Torrado & Vaudrevange (2013b); Fischer, Ramos-Sánchez & Vaudrevange (2013a)
Z\textsubscript{2} orbifold pillow

Starting point: torus
What is an orbifold?

$\mathbb{Z}_2$ orbifold pillow
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Z₂ orbifold pillow
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Challenges for particle physics from strings

Heterotic orbifolds

What is an orbifold?

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An orbifold is a space which is smooth/flat everywhere except for special \textit{(orbifold fixed) points}.
An orbifold is a space which is smooth/flat everywhere except for special (orbifold fixed) points

‘Bulk’ gauge symmetry $G$ is broken to (different) subgroups (local GUTs) at the fixed points
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‘Bulk’ gauge symmetry $G$ is broken to (different) subgroups (local GUTs) at the fixed points.

Low–energy gauge group: $G_{\text{low–energy}} = G_{\text{bl}} \cap G_{\text{br}} \cap G_{\text{tl}} \cap G_{\text{tr}}$
## Strings on orbifolds

<table>
<thead>
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<th>field theory</th>
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<td><strong>untwisted sector</strong> = strings closed on the torus</td>
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("Brane") Fields living at a fixed point with a certain symmetry appear as complete multiplet of that symmetry.
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- (‘Brane’) Fields living at a fixed point with a certain symmetry appear as complete multiplet of that symmetry
- E.g. if the electron lives at a point with $SO(10)$ symmetry also $u$ and $d$ quarks live there
String compactifications with local $SO(10)$ GUTs
String compactifications with local $\text{SO}(10)$ GUTs

6D internal space

4D space–time
String compactifications with local $SO(10)$ GUTs

6D internal space

$4D \text{ space–time}$

$SO(10)$

$16$
The mini–landscape search
Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

No exotics

### Results

1. **$3 \times 16 + \text{Higgs} + \text{nothing}$**

2. **$\text{SU}(3) \times \text{SU}(2) \times U(1)_Y \times G_{\text{hid}}$**

Results

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \times G_{\text{hid}}$

3. unification
   precision gauge unification (PGU)
   from non–local GUT breaking

Challenges for particle physics from strings

Heterotic orbifolds

Results & “stringy surprises”

Results

\[ 3 \times 16 + Higgs + \text{nothing} \]

\[ SU(3) \times SU(2) \times U(1) \]

\[ Y \times G \]

\[ \tilde{\text{unification}} \]

R parity & \[ \mathbb{Z}_4 \]

\[ \text{see–saw} \]

\[ t \approx g \]

\[ \log \frac{\Lambda}{\text{GeV}} \]

\[ 0.02 \]

\[ 0.03 \]

\[ 0.04 \]

\[ 0.05 \]

\[ 0.06 \]

\[ 0.07 \]

\[ 0.08 \]

\[ 0.09 \]

\[ \alpha_i \]

\[ \alpha_3 \]

\[ \alpha_2 \]

\[ \alpha_1 \]

\[ \text{Froggatt-Nielsen} \]

\[ \text{‘realistic’ hidden sector} \]

\[ \mu \text{ problem} \]

\[ \text{realistic flavor structures à la Froggatt-Nielsen} \]

\[ \text{Raby, M.R. & Schmidt-Hoberg (2010); Krippendorf, Nilles, M.R. & Winkler (2013)} \]
Results

1. $3 \times 16 + $ Higgs + nothing
2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$
3. unification
4. $R$ parity & $\mathbb{Z}_4^R$

$\sim$ proton long–lived
$\sim$ DM stable

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$\sim$ suppressed $\nu$ masses

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6. $y_t \approx g \, @ \, M_{\text{GUT}}$ $\&$ potentially realistic flavor structures à la Froggatt-Nielsen

$\sim$ realistic top mass

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7. ‘realistic’ hidden sector

scale of hidden sector strong dynamics is consistent with TeV–scale soft masses

Results & “stringy surprises”

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6. $y_t \simeq g @ M_{\text{GUT}}$ & potentially realistic flavor structures à la Froggatt-Nielsen
7. ‘realistic’ hidden sector
8. solution to the $\mu$ problem

$\mu \sim \langle W \rangle$

$\langle W \rangle \ll 1$ from approximate $\text{U}(1)_R$ symmetries

$\sim$ light Higgs

Results & “stringy surprises”

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that’s what we searched for...

that’s what we got ‘for free’

“stringy surprises”
Open questions & challenges
Open questions & challenges

Issue 1: the ‘Landscape’

PRO

Hard to disprove

Seems to have suggested the observed cosmological constant

Extremely convenient

CONTRA

There are observations that do not have an anthropic explanation such as $\theta_{\text{QCD}}$

see, however, Kaloper & Terning (2017)

A new version of “why now problem”: why did questions in the old days have non–anthropic explanations and only the newer problems not?

Note:

Even if one believes in the landscape, one still needs to understand the string models, i.e. construct at least some of them explicitly

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Even if one believes in the landscape, one still needs to understand the string models, i.e. construct at least some of them explicitly.
Issue 2: the ‘Swampland’

Swampland: constructions which resemble string constructions but are not

Vafa (2005)
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Swampland: constructions which resemble string constructions but are not

Example 1:
- infinite sets of models allowed by the usual consistency conditions of Calabi–Yau model building by adding fluxes...
- ...but these models would have an arbitrarily large number of massless states and cannot be UV complete

Vafa (2005)

Groot Nibbelink, Loukas, Ruehle & Vaudrevange (2015)
Issue 2: the ‘Swampland’

- Swampland: constructions which resemble string constructions but are not.
  
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- Example 1: constraints on fluxes???
  
- Example 2: 
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Swampland: constructions which resemble string constructions but are not

Example 1: constraints on fluxes???

Example 2:
- freely acting Wilson lines are subject to modular invariance constraints in orbifolds
- ...these orbifolds can be blown up to Calabi–Yau manifolds...
- ...but in Calabi–Yau model building there appear to be no analogous constraints

Vafa (2005)
e.g. Groot Nibbelink, Klevers, Plöger, Trapletti & Vaudrevange (2008)
Challenges for particle physics from strings

Open questions & challenges

Issue 2: the ‘Swampland’

Swampland: constructions which resemble string constructions but are not

Example 1: constraints on fluxes???

Example 2: constraints on Wilson lines?

Question: how many of the Calabi–Yau and F–theory models are truly consistent string models?

Question: are there additional consistency conditions at the level of field theory that ensure that a given model has a stringy completion?

... obviously globally consistent string compactifications fulfill this ...
Issue 3: Did we already find the standard model?

There is a number of known constructions that have not yet been ruled out.
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- However, we are still very far from calculating, say, the electron mass.
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- Would need to have better understanding of:
  - Kähler potential

see talk by Yessenia Olguin–Trejo
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see talk by Yessenia Olguin–Trejo
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However, we are still very far from calculating, say, the electron mass.

Would need to have better understanding of:

1. Kähler potential
2. Couplings at higher orders
3. Supersymmetry breaking

— see talk by Yessenia Olguin-Trejo
Issue 4: Where is supersymmetry?

So far no sign of supersymmetry at the LHC
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So far no sign of supersymmetry at the LHC

Should one focus on nonsupersymmetric string compactifications?

Kachru, Kumar & Silverstein (1999); Dienes (2001); Angelantonj & Antoniadis (2004); Dudas & Timirgaziu (2004); Dienes (2006)
Gato-Rivera & Schellekens (2007); Faraggi & Tsulaia (2008); Blaszczyk, Groot Nibbelink, Loukas & Ramos-Sánchez (2014)
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  ...but why has this been missed in the bottom–up approach?
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  ... but why has this been missed in the bottom–up approach?

- Tension between non–supersymmetric compactifications and a small cosmological constant
  
  Groot Nibbelink, Loukas, Mütter, Parr & Vaudrevange (2017)
Issue 5: Moduli stabilization

Explicit string models typically have many scalar fields which have a flat potential at the classical level.
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- Explicit string models typically have many scalar fields which have a flat potential at the classical level.
- Nontrivial potential often gets induced nonperturbatively.
- Challenge: enumerate and compute the local minima.
- Moduli VEVs determine couplings of the low–energy effective theory.

\[ \mathcal{L}_{\text{QCD}} \quad \xrightarrow{\text{very hard}} \quad \text{proton mass} \]

\[ \text{string model} \quad \xrightarrow{\text{much harder}} \quad \text{electron mass} \]
Issue 6: potential absence of smoking gun signatures

\[ \mathbb{Z}_4 \] symmetry:

- no dimension 4 proton decay
- dimension 5 proton decay negligible

Mütter, M.R. & Vaudrevange (2016)
Issue 6: potential absence of smoking gun signatures

\( \mathbb{Z}_4^R \) symmetry:
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non-local GUT breaking:
no dimension 6 proton decay!
**Issue 6: potential absence of smoking gun signatures**

**$\mathbb{Z}_4$ symmetry:**
- no dimension 4 proton decay
- dimension 5 proton decay negligible

**non–local GUT breaking:**
no dimension 6 proton decay!

**combined:**
amostly no proton decay

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Mütter, M.R. & Vaudrevange (2016)

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**Issue 6: potential absence of smoking gun signatures**

**\( \mathbb{Z}_4 \) symmetry:**
- no dimension 4 proton decay
- dimension 5 proton decay negligible

**non–local GUT breaking:**
no dimension 6 proton decay!

**combined:**
almost no proton decay

**however:**
proton decay is considered to be THE smoking gun signature of unification

\[ \begin{align*}
\overline{d}_{\text{red}}^{(1)} & \sim \overline{d}_{\text{red}}^{(2)} \\
\overline{d}_{\text{green}}^{(1)} & \sim \overline{d}_{\text{green}}^{(2)} \\
\overline{d}_{\text{blue}}^{(1)} & \sim \overline{d}_{\text{blue}}^{(2)} \\
\ell_{\uparrow}^{(1)} & \sim \ell_{\uparrow}^{(2)} + \ell_{\uparrow}^{(2)} \\
\ell_{\downarrow}^{(1)} & \sim \ell_{\downarrow}^{(2)} + \ell_{\downarrow}^{(2)}
\end{align*} \]
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Yet string theory does make some definite predictions:
1. all symmetries, including discrete ones, need to be anomaly–free
e.g. Witten (2017)
Summary

Despite considerable progress we do not yet have embedded the standard model into string theory.

Yet string theory does make some definite predictions:

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New methods such as machine learning may lead to further progress
Muchas gracias!

Enjoy the conference!


References II


References III


Challenges for particle physics from strings

References VI


References VII


