Model Building with Heterotic String Theory

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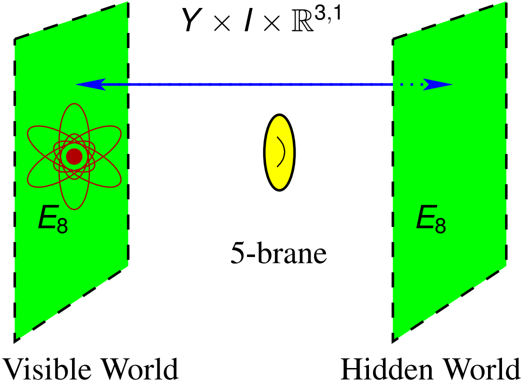
- Straightforward to break E_8 gauge symmetry
- Gauge unification without Yukawa unification
- Natural hidden sector, ideal place for SUSY breaking and/or dark matter

Heterotic M-theory



Y Calabi-Yau manifold (6-dimensional)
I Interval (1-dimensional)
$\mathbb{R}^{3,1}$ 4-d spacetime

Geometric Data

We need:

- A Calabi-Yau manifold Y.

  Polynomial equations in projective spaces.
  SUSY $\Leftrightarrow$ Kähler and $c_1(TY) = 0$.

- Vector bundles.

  Two basic constructions.
  SUSY $\Leftrightarrow$ slope-stable

Bundles on a Torus

Torus = Elliptic curve = Calabi-Yau 1-fold.

Atiyah classified the indecomposable bundles:

- Line bundles
- Extensions of line bundles

Line Bundles on a Torus

For simplicity: $c_1(\mathcal{L}) = 0 \;\Leftrightarrow\; \int F = 0.$

This fixes topology of the line bundle, but not its complex structure.

Theorem (Donaldson-Uhlenbeck-Yau)

$$\left\{ \begin{array}{c} \textit{Slope-stable} \\ \textit{holomorphic bundle} \end{array} \right\} \Leftrightarrow \left\{ \begin{array}{c} \textit{Solution to the} \\ \textit{Hermitian-Yang Mills} \\ \textit{equation} \end{array} \right\}$$

Line Bundles on a Torus

Fix a point $0 \in T^2$.

All line bundles (with $c_1 = 0$) are of the form

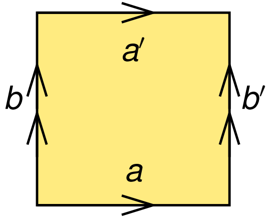
$$\mathcal{L} = \mathcal{O}_{T^2}(p - 0)$$

where p is a point in T^2.

- Algebraic point of view: There is a meromorphic section with a zero at 0 and a pole at p.
- Geometric point of view: The HYM connection has two $U(1)$ holonomies, parametrize a point $p \in T^2$.

Extension of Bundles

$T^2 =$



$\mathcal{O}_{T^2} = \mathcal{O}_{T^2}(0-0)$ has transition functions

$$\phi_{a,a'} = 1, \quad \phi_{b,b'} = 1$$

$\mathcal{O}_{T^2} \oplus \mathcal{O}_{T^2}$ has transition functions

$$\phi_{a,a'} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \phi_{b,b'} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Extension of Bundles

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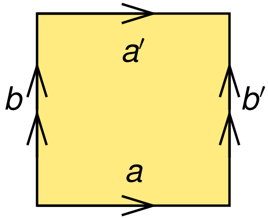

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Extension of Bundles

Define a new bundle with transition functions

$$\hat{\phi}_{a,a'} = \begin{pmatrix} 1 & 0 \\ \mathbf{1} & 1 \end{pmatrix}, \quad \hat{\phi}_{b,b'} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

- Embedding $f : (x) \mapsto (x, 0)$
- Projection $g : (y_1, y_2) \mapsto (y_2)$

Defines "extension" bundle

$$0 \longrightarrow \mathcal{O}_{T^2} \xrightarrow{f} \mathcal{A}^{(2)} \xrightarrow{g} \mathcal{O}_{T^2} \longrightarrow 0$$

For the experts: $\mathrm{Ext}^1(\mathcal{O}_{T^2}, \mathcal{O}_{T^2}) = \mathbb{C}$

Classification of Bundles on T^2

A rank-2 bundle[1] on T^2 is one of the following two possibilities:

- $\mathcal{O}_{T^2}(p_1 - 0) \oplus \mathcal{O}_{T^2}(p_2 - 0)$

  (Spectral cover)

- $\mathcal{O}_{T^2}(p - 0) \otimes \mathcal{A}^{(2)}$

  (Extension)

[1] with $c_1 = 0$ and a HYM connection

Spectral Covers on Calabi-Yau Threefolds

Use elliptically fibered Calabi-Yau threefold over a base surface. Patch together sums of line bundles on each fiber.

Local coordinates (x, y) on the base

$$\mathcal{V}\big|_{f_{(x,y)}} = \mathcal{O}_{T^2}\Big(p_1(x,y) - 0\Big) \oplus \mathcal{O}_{T^2}\Big(p_2(x,y) - 0\Big) \oplus \cdots$$

Bundle defined by the surface

$$\mathcal{C}_V = \big\{p_1(x,y) = 0\big\} \cup \big\{p_2(x,y) = 0\big\} \cup \cdots$$

Extensions on Calabi-Yau Threefolds

Rank-1 ingredients:

- Line bundles, defined by divisors (codimension 1)
- Sheaves, like bundles but with codimension ≥ 2 degenerations.

Extensions give higher rank bundles:

$$0 \longrightarrow \mathcal{L}_1 \longrightarrow \mathcal{V}^{(2)} \longrightarrow \mathcal{L}_2 \longrightarrow 0$$

Constructions

- Our "Heterotic Standard Model", MSSM via $SO(10)$ [Braun-HuiHe-Pantev-Ovrut]
- MSSM via $SU(5)$, using extensions of spectral covers [Bouchard-Donagi]
- Standard embedding + intermediate scale breaking [Greene-Kirklin-Miron-Ross]
- Orbifolds [Buchmuller-Hamaguchi-Lebedev-Ratz, Wingerter]
- U(n) bundles instead of SU(n) [Blumenhagen-Honecker-Weigand]
- Free fermions [Faraggi]

Particle Spectrum

The massless fields can be counted without knowing the metric and gauge connection explicitly.

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The massless fields can be counted without knowing the metric and gauge connection explicitly.

We found a Calabi-Yau manifold and slope-stable bundles with “nice” $4d$ low energy effective action:

- $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- 3 families of quarks and leptons
- No anti-families
- Anti-fivebrane breaks SUSY in hidden sector

Calabi-Yau Threefold

$\widetilde{X}$ is a complete intersection of 2 equations of degree $(3,0,1)$ and $(0,3,1)$ in $\mathbb{P}^2 \times \mathbb{P}^1 \times \mathbb{P}^2$.

[2] For suitable equations

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$$\Big\downarrow \text{quotient}$$

$$X = \widetilde{X}/\big(\mathbb{Z}_3 \times \mathbb{Z}_3\big) = \text{Calabi-Yau with } \pi_1(X) = \mathbb{Z}_3 \times \mathbb{Z}_3$$

[2] For suitable equations

Three Kähler moduli $t_1, t_2, t_3 \geq 0$ on X.

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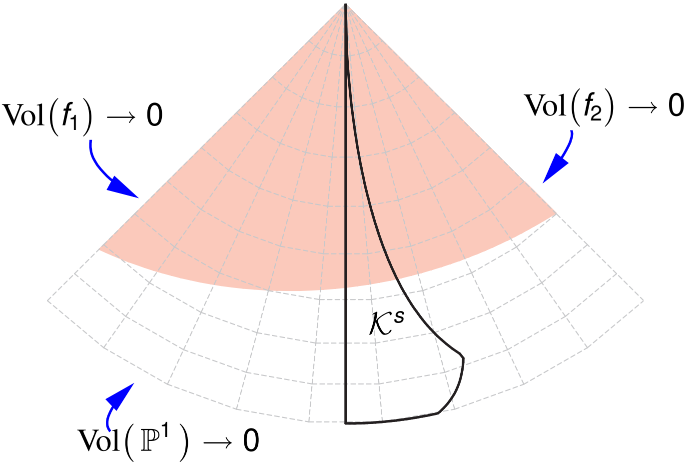
Cross-section of the Kählercone:



$$\mathrm{Vol}(X) = t_1 t_2 (t_1 + t_2 + 6 t_3)$$

Visible Sector Gauge Group

- Rank 4 vector bundle $\mathcal{V}$ breaks visible E_8 to $Spin(10)$.

$$\underline{\mathbf{248}} = (\underline{\mathbf{1}}, \underline{\mathbf{45}}) \oplus (\underline{\mathbf{15}}, \underline{\mathbf{1}}) \oplus (\underline{\mathbf{4}}, \underline{\mathbf{16}}) \oplus (\overline{\underline{\mathbf{4}}}, \overline{\underline{\mathbf{16}}}) \oplus (\underline{\mathbf{6}}, \underline{\mathbf{10}})$$

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- $\mathbb{Z}_3 \times \mathbb{Z}_3$ Wilson line breaks

$$Spin(10) \longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

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Each quark and lepton corresponds to a different $\underline{\mathbf{16}}$.

Doublet-Triplet Splitting

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$$\underline{\mathbf{10}} \longrightarrow \underbrace{\begin{matrix} (\underline{\mathbf{1}}, \underline{\mathbf{2}}, 3, 0) \\ (\underline{\mathbf{1}}, \underline{\bar{\mathbf{2}}}, -3, 0) \end{matrix}}_{\text{Higgs}} \begin{matrix} \oplus \\ \oplus \end{matrix} \underbrace{\begin{matrix} (\underline{\mathbf{3}}, \underline{\mathbf{1}}, -2, -2) \oplus \\ (\underline{\bar{\mathbf{3}}}, \underline{\mathbf{1}}, 2, 2) \end{matrix}}_{\text{Triplets}}$$

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On $\widetilde{X}$, there are

$$h^1\left(\widetilde{X}, \wedge^2 \mathcal{V}\right) = 4$$

$\underline{\mathbf{10}}$'s. Depending on the $\mathbb{Z}_3 \times \mathbb{Z}_3$ group action on each $\underline{\mathbf{10}}$, get either Higgs, triplet, or nothing.

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In our "heterotic standard model", all triplets are projected out while one Higgs (with its conjugate) is kept.

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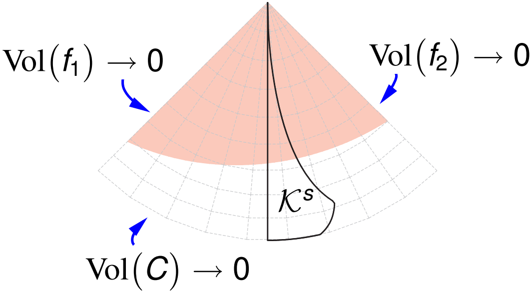

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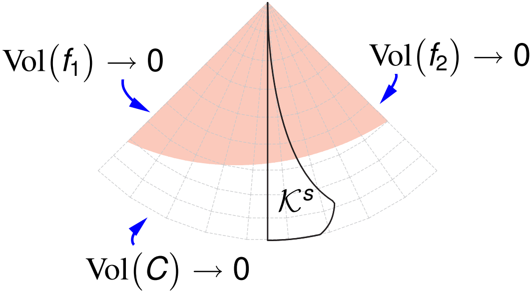

- Flip of $C \Leftrightarrow$ Decay into SUSY vacuum.

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In our “heterotic standard model”:

- Only two of the three families have Yukawa couplings
  $\Rightarrow$ One light family.
- No μ-term, avoids hierarchy problem.

Another Model

- Same Calabi-Yau manifold as before
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Leads to:

- Again 3 generations, no anti-generations
- Triplets still projected out
- But: 2 Higgs and 2 conjugate Higgs.

Massless Fields

Massless fields $\Leftrightarrow$ Bundle-valued one-forms.

Yukawa coupling

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In order for $Y_{ijk} \neq 0$, the three forms α_i, α_j, α_k must have legs in

- fiber 1 direction,
- fiber 2 direction, and
- base $\mathbb{P}^1$ direction.

Massless Fields

Origin	Direction	Field
$\underline{\mathbf{16}}$	Fiber 1	$Q_1,\ u_1,\ d_1,\ L_1,\ e_1,\ \nu_1$
$\underline{\mathbf{16}}$	Base	—
$\underline{\mathbf{16}}$	Fiber 2	$Q_{2,3},\ u_{2,3},\ d_{2,3},\ L_{2,3},\ e_{2,3},\ \nu_{2,3}$
$\underline{\mathbf{10}}$	Fiber 1	—
$\underline{\mathbf{10}}$	Base	$H_1,\ \bar{H}_1$
$\underline{\mathbf{10}}$	Fiber 2	$H_2,\ \bar{H}_2$

Yukawa Couplings

For example, up-quark mass matrix

$$\begin{pmatrix} 0 & \lambda_{u,12}\langle H_1\rangle & \lambda_{u,13}\langle H_1\rangle \\ \lambda_{u,21}\langle H_1\rangle & 0 & 0 \\ \lambda_{u,31}\langle H_1\rangle & 0 & 0 \end{pmatrix} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_1\langle H_1\rangle & 0 \\ 0 & 0 & \lambda_2\langle H_1\rangle \end{pmatrix}$$

$\Rightarrow$ One light generation of quarks and leptons.

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Second Higgs Pair

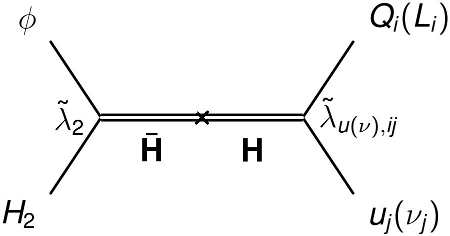
H_2, $\bar{H}_2$ has no Yukawa couplings except μ-term

$$W_\mu = \lambda_1 \phi H_1 \bar{H}_2 + \lambda_2 \phi H_1 \bar{H}_2$$

Beyond Tree-Level

The superpotential can have higher order terms:

- Integrating out massive Kaluza-Klein modes, for example



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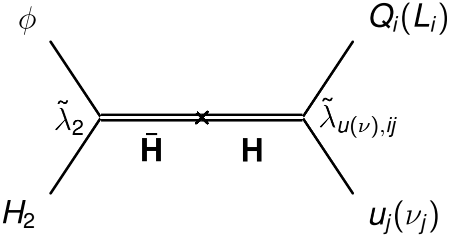

- Non-perturbative corrections.

But: Suppressed by $\frac{1}{M_c}$.

μ-Term and Moduli Vevs

Classical μ-term:

$$W_\mu = \lambda_1 \phi H_1 \bar{H}_2 + \lambda_2 \phi H_1 \bar{H}_2$$

Not all moduli ϕ appear, but those that do must have really small vev.

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Quartic term

$$W_\mu = \frac{\lambda_{mnij}}{M_c} \phi_m \phi_n H_i \bar{H}_j$$

must be electroweak scale, hence

$$\frac{\left(\tilde{\lambda}^2\right)^2}{M_c} \langle \phi_m \rangle \langle \phi_n \rangle \lesssim M_{\text{EW}} \quad \Leftrightarrow \quad \tilde{\lambda}^2 \frac{\langle \phi \rangle}{M_c} \lesssim \sqrt{\frac{M_{\text{EW}}}{M_c}} \approx 10^{-7}$$

Simplified Model

Take normal (non-SUSY) Standard Model and add

- Single scalar ϕ
- second Higgs H_2
- $\mathbb{Z}_2$ symmetry $\phi \mapsto -\phi$, $H_2 \mapsto -H_2$.
- Dimension 5 operators

$$\mathcal{L}_5 = \tilde{\lambda}_{u,ij} \frac{\phi}{M_c} \bar{Q}_i H_2^* u_j + \tilde{\lambda}_{d,ij} \frac{\phi}{M_c} \bar{Q}_i H_2 d_j + \\ + \tilde{\lambda}_{\nu,ij} \frac{\phi}{M_c} \bar{L}_i H_2^* \nu_j + \tilde{\lambda}_{e,ij} \frac{\phi}{M_c} \bar{L}_i H_2 e_j + \text{h.c.}$$

with couplings $\lesssim 10^{-7}$.

Result

We obtain FCNC-induced mass splittings of mesons

F^0	$\Delta M_F^{SM} / GeV$	$\Delta M_F^{Exp} / GeV$	$\Delta M_F^{2-\text{Higgs}} / GeV$
K^0	$1.4 - 4.6 \times 10^{-15}$	3.51×10^{-15}	4.72×10^{-19}
B_d^0	$10^{-13} - 10^{-12}$	3.26×10^{-13}	$.88 \times 10^{-20}$
D^0	$10^{-17} - 10^{-16}$	$< 1.32 \times 10^{-13}$	4.56×10^{-21}

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Flavor-changing neutral currents are far below the Standard Model contributions.

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