

BSM phenomenology from heterotic string orbifolds

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Workshop STRONG-2020 & HFHF theory retreat

October 3rd, 2023



- 1 Beyond the Standard Model
- 2 Heterotic Orbifolds in String Theory
- 3 Phenomenology of orbifold compactifications
 - Higgs-portal DM
- 4 Conclusions

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SM irreps

f	irrep
q	$(\mathbf{3}, \mathbf{2})_{1/6}$
ℓ	$(\mathbf{1}, \mathbf{2})_{-1/2}$
\bar{u}	$(\bar{\mathbf{3}}, \mathbf{1})_{-2/3}$
\bar{d}	$(\bar{\mathbf{3}}, \mathbf{1})_{1/3}$
\bar{e}	$(\mathbf{1}, \mathbf{1})_1$

s	irrep
ϕ	$(\mathbf{1}, \mathbf{2})_{1/2}$

V_μ	irrep
G_μ^a	$(\mathbf{8}, \mathbf{1})_0$
W_μ^a	$(\mathbf{1}, \mathbf{3})_0$
B_μ	$(\mathbf{1}, \mathbf{1})_0$

- SM irreps under $\mathcal{G}_{\text{SM}} = \text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y$.

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BSM

- SM as an **effective theory**
 - Quantum gravity effects become relevant at $M_P \sim 10^{19}$ GeV
- Already known BSM physics:
 - Neutrino masses \Rightarrow mixing
 - Muon anomalous magnetic moment
 - Particle physics description of **dark matter (DM)**
- **Naturalness** and **hierarchy** problems:
 - Mass hierarchy
 - Electroweak hierarchy problem
 - Strong CP problem

BSM

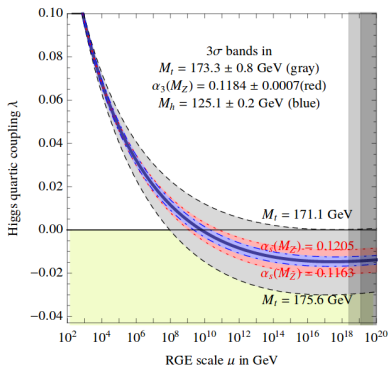
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- Bottom-up vs top-down
 - Higgs portals, Z' models
 - Supersymmetry (SUSY), String Theory

Higgs vacuum meta-stability

The Higgs quartic coupling $\lambda(\mu) < 0$ at $\mu \sim 10^{10}$ GeV

D. Buttazzo [arXiv:1307.3536].

- Potential becomes unbounded from below, **no minimum**.
- **Decay** to vacuum with different physics.



Qualitatively, for small λ

$$\beta(\lambda) \propto \sum_{i,j=1,2} g_i^2 g_j^2 - h_t^4 < 0$$

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String Theory

- 1D objects propagating in D -dim spacetime
 - Scalar fields on the worldsheet $X^M(\tau, \sigma)$ $M = 0, 1, \dots, D - 1$
 - Action = worldsheet area \rightarrow wave equations
 - $\alpha_n^M, \tilde{\alpha}_n^M$ oscillation modes
 - CFT \rightarrow requires gauge fixing

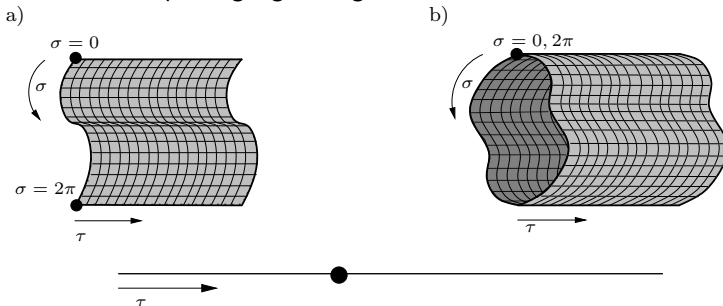
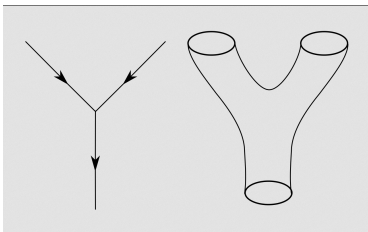


Figure: Worldsheets of a) open and b) closed string. Particle's worldline (down).

String Theory

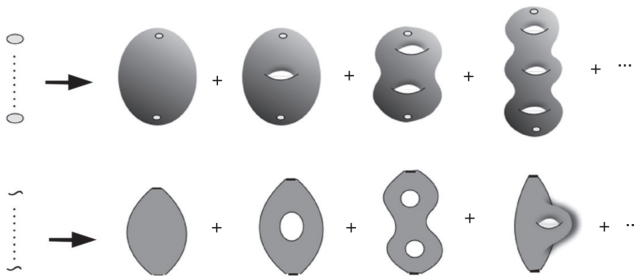
- 1D objects propagating in D -dim spacetime
- Quantization
 - $\alpha_n^M, \tilde{\alpha}_n^M$ creation/annihilation operators
 - Anomalies absent only when $D = 26$
 - Interactions already included → No UV divergences
 - Low energy limit: string modes become quantum fields
 - QFT dynamics recovered: KG, YM, Einstein



¹Ibanez, Uranga, *String theory and particle physics: An introduction to string phenomenology*

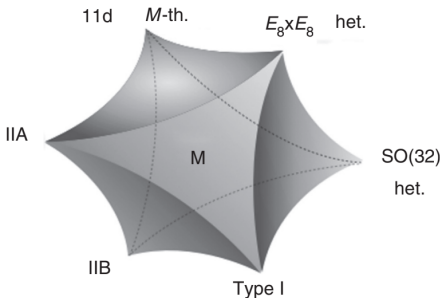
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String Theory

- 1D objects propagating in D -dim spacetime
- Quantization
- Disadvantages:
 - No fermions → SUSY
 - $D = 10$ → Compactification
 - 5 superstring theories → M theory unification (dualities)



Heterotic String

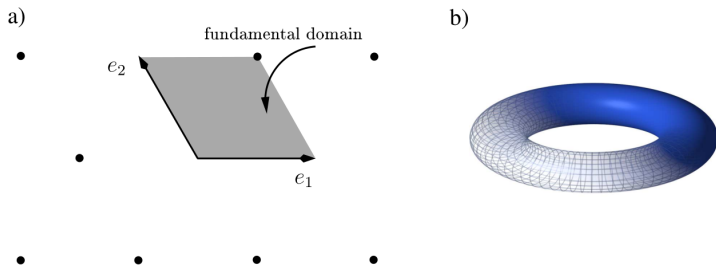
Heterotic String	Right modes	Left modes	
$\mu = 0, 1, 2, 3$	X_R^μ, Ψ_R^μ	X_L^μ	4D spacetime
$m = 4, 5, \dots, 9$	X_R^m, Ψ_R^m	X_L^m	$\mathcal{O} = \mathbb{T}^6/\mathcal{P} = \mathbb{R}^6/\mathcal{S}$
$I = 10, 11, \dots, 25$	–	X_L^I	\mathbb{T}^{16}

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- Momenta in the torus $p = (p^I) \in \Lambda_{\mathbf{E}_8 \times \mathbf{E}_8}$ or $\Lambda_{\text{SO}(32)}$ ($\mathcal{N} = 1$ SUSY)
- Compactify 6 dimensions in a toroidal orbifold \mathcal{O}
- Non-supersymmetric heterotic string with gauge group $\text{SO}(16) \times \text{SO}(16)$

2D Torus



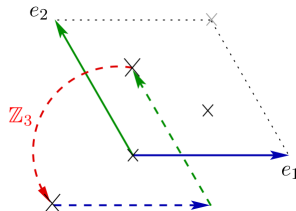
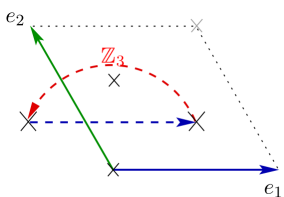
1

- Lattice $\Gamma = \{n_\alpha e_\alpha | n_\alpha \in \mathbb{Z}, \alpha = 1, 2\}$ generates \mathbb{T}^2
- Point identification $X \simeq X + n_\alpha e_\alpha$

¹Ramos, stringpheno.fisica.unam.mx

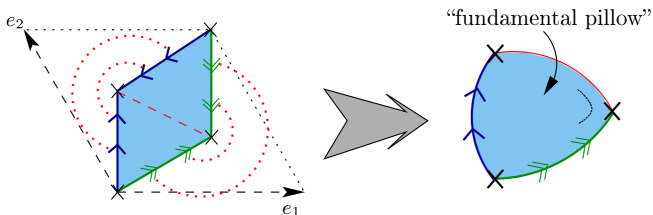
\mathbb{Z}_3 toroidal orbifold

- Add the action of a point group $\mathcal{P} = \mathbb{Z}_3$
- $\theta e_\alpha \in \Gamma$ for all $\theta \in \mathcal{P}$
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fundamental pillow = ravioli



6D Torus \rightarrow 6D Orbifold

- $\mathbb{T}^6 = \mathbb{T}^2 \times \mathbb{T}^2 \times \mathbb{T}^2$
- $\Gamma = \{n_\alpha e_\alpha \mid n_\alpha \in \mathbb{Z}, \alpha = 1, \dots, 6\}$
- Twist $\theta = \vartheta^k \in \mathcal{P} = \mathbb{Z}_N, k \in \mathbb{Z}$
- Space group $\mathcal{S} = \mathcal{P} \ltimes \Gamma, g = (\theta, n_\alpha e_\alpha) \in \mathcal{S}$
- Complex coordinates $\vartheta = \text{diag}(e^{2\pi i v^1}, e^{2\pi i v^2}, e^{2\pi i v^3})$
then $v = (0, v^1, v^2, v^3)$

Constraints

- **Embedding** of the orbifold action
 - $\mathcal{S} \hookrightarrow \mathcal{G}$ such that
$$g = (\vartheta^k, n_\alpha e_\alpha) \mapsto (kV, n_\alpha A_\alpha), \text{ with } k, n_\alpha \in \mathbb{Z}$$
 - $X^I \rightarrow X^I + kV^I + n_\alpha A_\alpha^I, I = 10, \dots, 25$
with $NV, NA_\alpha \in \Lambda$
 - **WL**: gauge transformations associated to non-contractible loops in each direction e_α of the torus

Constraints

- **Embedding** of the orbifold action
- **Supersymmetry** and **modular invariance**
 - SUSY $\mathcal{N} = 1$ in 4D \rightarrow holonomy $SU(3) \supset \mathcal{P}$ then
 $v^1 + v^2 + v^3 = 0$
 - Modular invariance of the **1-loop partition function** implies

$$N(V^2 - v^2) = 0 \pmod{2},$$

$$N_\alpha(A_\alpha \cdot V) = 0 \pmod{2},$$

$$N_\alpha(A_\alpha^2) = 0 \pmod{2},$$

$$\gcd(N_\alpha, N_\beta)(A_\alpha \cdot A_\beta) = 0 \pmod{2} \quad (\alpha \neq \beta),$$

where $N_\alpha A_\alpha \in \Lambda$.

Constraints

- **Embedding** of the orbifold action
- **Supersymmetry** and **modular invariance**
- **Compatibility** of the orbifold action with the Hilbert space
 - In \mathcal{H}_g the states satisfy $Z(\tau, \sigma + 2\pi) = gZ(\tau, \sigma)$, $g \in \mathcal{S}$
 - Then hZ with $h \in \mathcal{Z}_g \equiv \{h \in \mathcal{S} | [g, h] = 0\}$ defines the **same state**
 - The action

$$|q_{\text{sh}}\rangle_R \otimes \alpha |p_{\text{sh}}\rangle_L \xrightarrow{h} e^{2\pi i \varphi} |q_{\text{sh}}\rangle_R \otimes \alpha |p_{\text{sh}}\rangle_L,$$

implies the constraint $\varphi = 0 \pmod{1}$

Constraints

- **Embedding** of the orbifold action
- **Supersymmetry** and **modular invariance**
- **Compatibility** of the orbifold action with the Hilbert space
- orbifolder to calculate the massless spectrum of viable models **Nilles et al. [arXiv:1110.5229]**

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- *Higgs-portal dark matter from non-supersymmetric strings*, Esau Cervantes, O. P.–F., Ricardo Perez–Martinez and Saul Ramos–Sanchez, Phys. Rev. D **107**, 115007 (2023) .
arXiv:2302.08520 [hep-ph].



Scenario

- **Non-SUSY** heterotic string $SO(16) \times SO(16)$
in toroidal orbifold $\mathbb{Z}_2 \times \mathbb{Z}_4(2, 4)$
- $\mathcal{G}_{4D} = \mathcal{G}_{SM} \times \mathcal{G}' \times [U(1)']^8$ with $\mathcal{G}' = \mathcal{G}_{\text{flavor}} \times \mathcal{G}_{\text{hidden}}$
- Massless spectrum: **SM + scalar singlets + few heavy exotics**
 - More than one Higgs or several fermion exotics
(Higgs portal models \rightarrow prolific DM scenarios)
- **freeze-out** drives DM production

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 - DM particle out of thermal equilibrium when the expansion of the Universe is faster than the interaction rate for the processes $DM \longleftrightarrow SM$

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 - Massless spectrum: **SM + scalar singlets + few heavy exotics**
 - More than one Higgs or several fermion exotics
(Higgs portal models \rightarrow prolific DM scenarios)
 - **freeze-out** drives DM production
 - Goals: Identify the Higgs-portal scenario with
 - DM relic density below bounds
 - stable Higgs vacuum
 - reproduces the observed Higgs mass and VEV
- if successful, predict the mass of the DM candidate and the heavy Higgs spectrum

A stringy THDM

- $\mathcal{G}_{4D} = \mathcal{G}_{SM} \times SU(2)_{\text{flavor}} \times [SU(3) \times SU(2)]_{\text{hidden}} \times [U(1)]^8$
(where $\mathcal{G}_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$)

#	Fermionic irrep.	Label
3	$(\mathbf{1}, \mathbf{2}; \mathbf{1})_{-1/2}$	$\ell_{L,i}$
1	$(\mathbf{1}, \mathbf{1}; \mathbf{2})_1$	\bar{e}_L
1	$(\mathbf{1}, \mathbf{1}; \mathbf{1})_1$	$\bar{e}_{L,3}$
1	$(\mathbf{3}, \mathbf{2}; \mathbf{2})_{1/6}$	q_L
1	$(\mathbf{3}, \mathbf{2}; \mathbf{1})_{1/6}$	$q_{L,3}$
1	$(\bar{\mathbf{3}}, \mathbf{1}; \mathbf{2})_{-2/3}$	\bar{u}_L
1	$(\bar{\mathbf{3}}, \mathbf{1}; \mathbf{1})_{-2/3}$	$\bar{u}_{L,3}$
5	$(\bar{\mathbf{3}}, \mathbf{1}; \mathbf{1})_{1/3}$	$\bar{d}_{L,i}$
2	$(\mathbf{3}, \mathbf{1}; \mathbf{1})_{-1/3}$	$d'_{L,i}$
131	$(\mathbf{1}, \mathbf{1}; \mathbf{1})_0$	$\nu_{R,i}$
14	$(\mathbf{1}, \mathbf{1}; \bar{\mathbf{2}})_0$	$\nu'_{R,i}$

#	Scalar irrep.	Label
2	$(\mathbf{1}, \mathbf{2}; \mathbf{1})_{1/2}$	ϕ_i
1	$(\mathbf{1}, \mathbf{1}; \mathbf{1})_0$	S
107	$(\mathbf{1}, \mathbf{1}; \mathbf{1})_0$	s_i
8	$(\mathbf{1}, \mathbf{1}; \mathbf{2})_0$	s'_i
2	$(\bar{\mathbf{3}}, \mathbf{1}; \mathbf{2})_{1/3}$	x_i

- At tree level:
 - masses for extra $d'_{L,i}$
 - Yukawa couplings such that the heaviest quarks and lepton can be identified
 - Leptoquark x_i interactions

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 - masses for extra $d'_{L,i}$
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 - Leptoquark x_i interactions
 - **Potential:** Higgs + Singlet DM candidate + Interaction

$$\begin{aligned}
 V_\phi(\phi_1, \phi_2) = & \mu_{11}^2 |\phi_1|^2 + \mu_{22}^2 |\phi_2|^2 + \lambda_1 |\phi_1|^4 + \lambda_2 |\phi_2|^4 + \lambda_3 |\phi_1|^2 |\phi_2|^2 \\
 & + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1) + \left[\mu_{12}^2 \phi_1^\dagger \phi_2 + \lambda_5 (\phi_1^\dagger \phi_2) (\phi_1^\dagger \phi_2) \right. \\
 & \left. + \lambda_6 |\phi_1|^2 (\phi_1^\dagger \phi_2) + \lambda_7 |\phi_2|^2 (\phi_1^\dagger \phi_2) + \text{h.c.} \right],
 \end{aligned}$$

$$V_S(S) = \mu_S^2 |S|^2 + \lambda_S |S|^4,$$

$$\begin{aligned}
 V_{\phi S}(\phi, S) = & \lambda_{1S} |\phi_1|^2 |S|^2 + \lambda_{2S} |\phi_2|^2 |S|^2 \\
 & + \lambda_{12S} \left[(\phi_2^\dagger \phi_1) |S|^2 + \text{h.c.} \right]
 \end{aligned}$$

- Upon EWSB

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \longrightarrow \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \sigma_1) \end{pmatrix} \quad \text{and}$$
$$\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \longrightarrow \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \sigma_2) \end{pmatrix}$$

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- Higgs spectrum
 - Neutral heavy and light scalars h, H
 - Pseudoscalar A
 - Charged Higgs H^\pm
- DM mass

Fitting DM and Higgs data

- Higgs-vacuum stability at 1-loop
- Admissibly heavier states in the Higgs sector
- Compatibility with observables
PDG 2022, Planck collab. 2018 [[arXiv:astro-ph/1807.06209](https://arxiv.org/abs/1807.06209)]

$$m_h = 125.25(17) \text{ GeV},$$

$$v = 246.219640(63) \text{ GeV},$$

$$\Omega_{\text{DM}} h^2 = 0.120(1),$$

where $v = (\sqrt{2}G_F)^{-1/2}$ and in our model $v^2 = v_1^2 + v_2^2$

- χ^2 minimization

Fitting DM and Higgs data

- Higgs-vacuum stability at 1-loop
- Admissibly heavier states in the Higgs sector
- Compatibility with observables
- χ^2 minimization
As usual we define

$$\chi_\mu = \frac{y_\mu^{\text{meas}} - y_\mu^{\text{model}}(\mathbf{p})}{\sigma_\mu}, \quad \text{such that} \quad \chi^2 := \sum_{\mu=1}^3 \chi_\mu^2$$

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- χ^2 minimization
- Parameters

$$\mu_{12}^2, \tan \beta = v_2/v_1, \lambda_i, \quad (i = 1, \dots, 7)$$

$$\mu_S^2, \lambda_S, \lambda_{1S}, \lambda_{2S}, \lambda_{12S}$$

Numerical tools

SARAH generates input files for

- VevaciousPlusPlus determines the **Higgs VEVs** (v_1, v_2) at several identified vacua and **stability status**
Camargo and O'Leary,
<https://github.com/JoseEliel/VevaciousPlusPlus>
- SPheno 4.0.5 computes the **mass spectrum** including 1-loop corrections
Porod [arXiv:hep-ph/0301101], [arXiv:1104.1573]
- micrOMEGAs 5.3.35 computes the freeze-out **DM relic abundance**, including 1-loop annihilation processes
Belanger et al. [arXiv:1801.03509]

Parameter scan

- Random scan over Higgs potential params and bisection method to determine $\tan \beta$ for the correct m_h at 6σ
 $\rightarrow \chi^2 \sim 10^4$
- Scan over all parameters with **optimization methods** implemented in Python (package LMFIT [Newville et al. Imfit/Imfit-py: 1.1.0](#))
 - Differential evolution: global
 - Least squares: local $\rightarrow \chi^2 = 7.6$
- Markov Chain Monte Carlo **ensemble sampler**: exploration of a neighborhood of promising parameter space points
 $\rightarrow \chi^2 = 1.23 \times 10^{-4}$

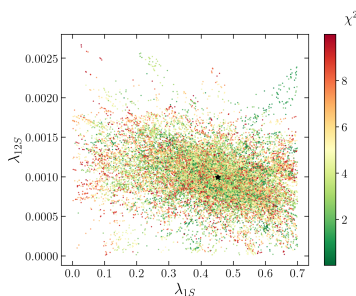
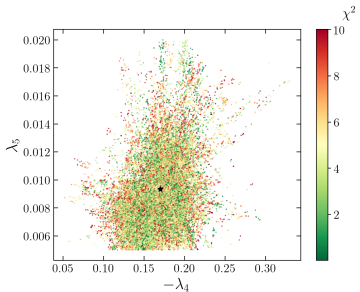
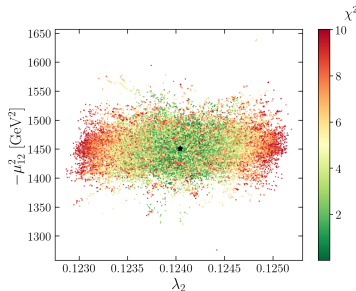
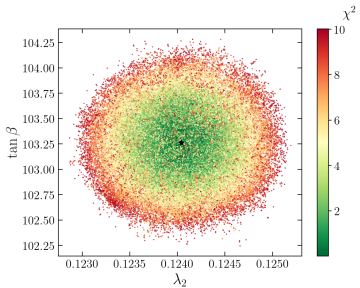
Results: best fit

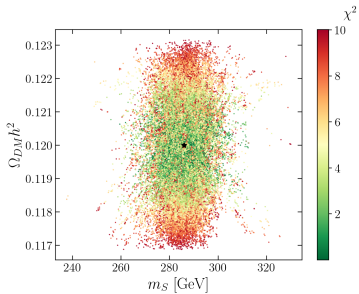
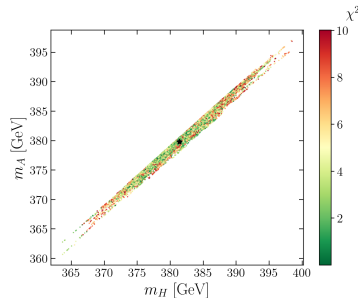
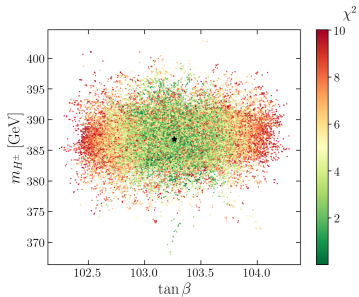
Higgs parameter	value
λ_1	3.63×10^{-4}
λ_2	1.24×10^{-1}
λ_3	5.03×10^{-1}
λ_4	-1.7×10^{-1}
λ_5	9.35×10^{-3}
λ_6	5.52×10^{-4}
λ_7	3.76×10^{-4}
μ_{12}^2	$-1.45 \times 10^3 \text{ GeV}^2$
v_1	2.394 GeV
v_2	246.21 GeV

Higgs-portal parameter	value
μ_S^2	$7.77 \times 10^4 \text{ GeV}^2$
λ_S	8.33×10^{-3}
λ_{1S}	4.52×10^{-1}
λ_{2S}	1.18×10^{-1}
λ_{12S}	9.95×10^{-4}

observable	value
m_h	125.25 GeV
m_H	381.41 GeV
m_{H^\pm}	386.82 GeV
m_A	379.82 GeV
$\Omega_{\text{DM}} h^2$	0.12
m_S	286.01 GeV
χ^2	1.23×10^{-4}

$$\tan \beta = 102.84$$





- 1 Beyond the Standard Model
- 2 Heterotic Orbifolds in String Theory
- 3 Phenomenology of orbifold compactifications
 - Higgs-portal DM
- 4 Conclusions

- **String theory** is a strong candidate for a UV completion of the SM, it may describe quantum gravity but it is not fully understood and it is not clear yet that nature is described by it.
- Effective vacua of string compactifications may possess the correct ingredients to solve SM extant problems.
- Non-SUSY heterotic string compactifications with point group $\mathbb{Z}_2 \times \mathbb{Z}_4$ lead to effective Higgs portal models. A parameter scan performed for a THDM shows that the **correct DM relic abundance** can be fitted for the parameters with a singlet scalar candidate while **stabilizing the Higgs vacuum**.
- The effective models explored in both works can also be seen as **bottom-up** proposals and other models found in this context may possess interesting phenomenology that is left to be researched.

Thanks!

Thanks!
Questions?

- 5 Backup slides
- 6 Gauge coupling of $U(1)'$ models

A word about SUSY

- SUSY
 - $N_f = N_b$
 - Suggests GUTs: gauge coupling unification
 - Solves the EW hierarchy problem

ST in detail: Action and Symmetries

- 1D objects propagating over spacetime, described in the worldsheet $X^M(\tau, \sigma)$ in D dims $M = 0, 1, \dots, D - 1$

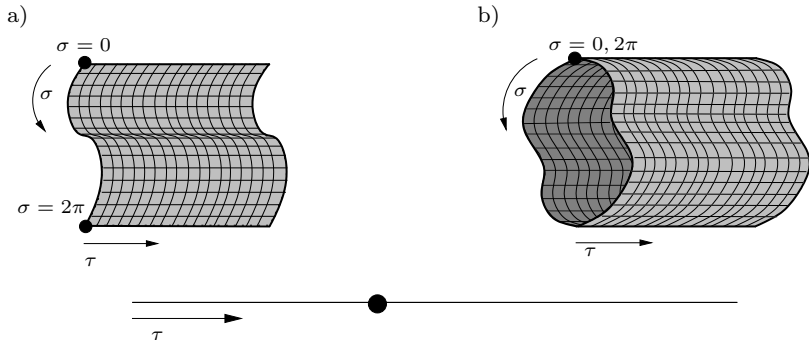


Figure: Worldsheets of an a) open and a b) closed string in comparison with a particle's worldline (down).

ST in detail: Action and Symmetries

- 1D objects propagating over spacetime, described in the worldsheet $X^M(\tau, \sigma)$ in D dims $M = 0, 1, \dots, D - 1$
- Nambu-Goto action (worldsheet area) non-polynomial \rightarrow Polyakov action via worldsheet metric

$$\mathcal{S}_{\text{NG}}[X] = -\frac{1}{2\pi\alpha'} \int d\tau d\sigma \sqrt{-\det \partial_a X^M \partial_b X^N g_{MN}(X)}$$

String tension $T = 1/(2\pi\alpha')$ (Regge slope α')

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$$S_P[X, g_{ab}] = -\frac{1}{4\pi\alpha'} \int d\tau d\sigma \sqrt{-\det(g^{ab})} g^{ab} \partial_a X^M \partial_b X^N g_{MN}(X)$$

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- Symmetries...
 - Spacetime reparams (diffeos) $x^M \rightarrow \bar{x}^M(x)$ then $X^M(\tau, \sigma) \rightarrow \bar{X}^M(\tau, \sigma) = \bar{x}(X(\tau, \sigma))$
 - Worldsheet reparametrizations $\sigma^a \rightarrow \bar{\sigma}^a(\sigma)$
 - Weyl transformations (intrinsic metric rescaling) $g_{ab}(\sigma) \rightarrow \bar{g}_{ab}(\sigma) = \Omega(\sigma)g_{ab}(\sigma)$

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 - Weyl transformations (intrinsic metric rescaling) $g_{ab}(\sigma) \rightarrow \bar{g}_{ab}(\sigma) = \Omega(\sigma)g_{ab}(\sigma)$
- Even after fixing some gauge freedom there is a remaining conformal symmetry \rightarrow CFT

ST in detail: Solutions

- Wave equations $(\partial_\tau^2 - \partial_\sigma^2)X^M = 0$ and boundary conditions of a closed $X^M(\tau, \sigma + 2\pi) = X^M(\tau, \sigma)$ or open string (Neumann and Dirichlet)

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- Solutions can be decomposed in left and right movers
 $X^M(\tau, \sigma) = X_L^M(\tau + \sigma) + X_R^M(\tau - \sigma)$

$$X_L^M(\sigma^+) = \frac{x^M}{2} + \sqrt{\frac{\alpha'}{2}}\alpha_0^M\sigma^+ + i\sqrt{\frac{\alpha'}{2}}\sum_{n\neq 0}\frac{\alpha_n^M}{n}e^{-in\sigma^+}$$

$$X_R^M(\sigma^-) = \frac{x^M}{2} + \sqrt{\frac{\alpha'}{2}}\tilde{\alpha}_0^M\sigma^- + i\sqrt{\frac{\alpha'}{2}}\sum_{n\neq 0}\frac{\tilde{\alpha}_n^M}{n}e^{-in\sigma^-}$$

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- Oscillation modes $\alpha_n^M, \tilde{\alpha}_n^M$ become creation and annihilation operators upon quantization
- String excitations (oscillation modes in spacetime) are particles of a QFT at low energy

Semi-direct product

Given two subgroups H and K of G , with $H \trianglelefteq G$ (for each $h \in H$, $[g, h] = 0$ for all $g \in G$), $H \cap K = \{1\}$ and $HK = G$, then we write $G = H \rtimes K$.

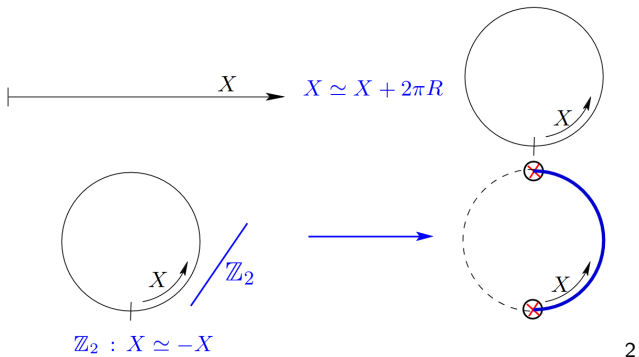
For the space group $\mathcal{S} = \mathcal{P} \rtimes \Gamma$ the action of the element $g = (\theta, \ell) \in \mathcal{S}$ (where $\theta = \vartheta^k$ for the Abelian case $\mathcal{P} = \mathbb{Z}_N$ and $\ell = n_\alpha e_\alpha$) is given by

$$gX = \theta X + \ell,$$

where the product $g_1 g_2 = (\theta_1, \ell_1)(\theta_2, \ell_2) = (\theta_1 \theta_2, \theta_1 \ell_2 + \ell_1) \in \mathcal{S}$ gives structure to the group. In general, elements of the point group do not commute with an arbitrary space group element since

$$(\theta_1 \theta_2, \theta_1 \ell_2) = (\theta_1, 0)(\theta_2, \ell_2) \neq (\theta_2, \ell_2)(\theta_1, 0) = (\theta_2 \theta_1, \ell_2).$$

1D orbifold



²Ramos, stringpheno.fisica.unam.mx

States for the massless spectrum

- **Right movers**

- States $\psi_{-1/2}^M |0\rangle_R$ in NS sector and $\psi_0^M |0\rangle_R$ in R ($M = 2, \dots, 9$) are $|q\rangle_R$ where q denotes the weight of the $SO(8)$ rep

$$|q\rangle_R = \begin{cases} |\pm 1, 0, 0, 0\rangle_R & \sim \mathbf{8}_v, & \mathbf{NS}, \\ |\pm \frac{1}{2}, \pm \frac{1}{2}, \pm \frac{1}{2}, \pm \frac{1}{2}\rangle_R & \sim \mathbf{8}_s, & \mathbf{R}. \end{cases}$$

- For massless states

$$\frac{\alpha' m_R^2}{4} = \frac{1}{2} q^2 - \frac{1}{2} = 0.$$

- **Left movers**

- States $\alpha_{-1}^M |0\rangle_L$, $\alpha_{-1}^I |0\rangle_L$ with $I = 10, \dots, 25$ or $|p\rangle_L$ where $p^2 = 2$.
- Massless states

$$\frac{\alpha' m_L^2}{4} = \frac{1}{2} p^2 + N - 1 = 0, \quad \text{where} \quad N = \sum_{n>0} (\alpha_{-n}^M \alpha_n^M + \alpha_{-n}^I \alpha_n^I).$$

Sectors details

- Non-twisted sector

- $Z(\tau, \sigma + 2\pi) = Z(\tau, \sigma) + n_\alpha e_\alpha, \quad n_\alpha \in \mathbb{Z}$
- States $|q\rangle_R \otimes \alpha_{-1}^x |p\rangle_L$ ($x = M = 2, \dots, 9$ or $x = I = 10, \dots, 25$) associated to $g = (\mathbb{1}, 0)$
- $\varphi = p \cdot V_h - q \cdot v_h + (\delta_{x,a} - \delta_{x,\bar{a}}) v_h^{a,\bar{a}}$ for an $h \in \mathcal{S}$

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- Twisted sector

- $Z(\tau, \sigma + 2\pi) = \vartheta^k Z(\tau, \sigma) + n_\alpha e_\alpha, \quad k = 1, \dots, N - 1.$
- States $|q_{\text{sh}}\rangle_R \otimes \alpha |p_{\text{sh}}\rangle_L$, associated to $g = (\vartheta^k, n_\alpha e_\alpha).$
- $|q_{\text{sh}}\rangle_R \otimes \alpha |p_{\text{sh}}\rangle_L \equiv |q + v_g\rangle_R \otimes \alpha |p + V_g\rangle_L$
with $v_g = kv$ and $V_g = kV + n_\alpha A_\alpha$

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- α denotes $\alpha_{-\eta^a}^a$ and $\alpha_{-1+\eta^a}^{\bar{a}}$ products
where $\eta^a = kv^a \bmod 1$ ($0 < \eta^a \leq 1$)

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- $\varphi = p_{\text{sh}} \cdot V_h - q_{\text{sh}} \cdot v_h + (N_g - N_g^*) \cdot v_h - \frac{1}{2}(V_g \cdot V_h - v_g \cdot v_h),$
 $h \in \mathcal{Z}_g$ **Plöger, Ramos, Vaudrevange, Ratz [arXiv:0702176]**

Sectors details

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- **Massless states** fulfill

$$\frac{\alpha' m_R^2}{4} = \frac{1}{2} q_{\text{sh}}^2 - \frac{1}{2} + \delta c \stackrel{!}{=} 0$$

and

$$\frac{\alpha' m_L^2}{4} = \frac{1}{2} p_{\text{sh}}^2 + N - 1 + \delta c \stackrel{!}{=} 0$$

with $\delta c = \frac{1}{2} \sum_a \eta^a (1 - \eta^a)$ and $N = \sum_{a=1}^3 \eta^a (N_g^a + N_g^{*\bar{a}})$

Massless spectrum of the non-twisted sector

- $Z(\tau, \sigma + 2\pi) = Z(\tau, \sigma) + n_\alpha e_\alpha, \quad n_\alpha \in \mathbb{Z}$
- States $|q\rangle_R \otimes \alpha_{-1}^x |p\rangle_L$ ($x = M, I$) associated to $g = (\mathbb{1}, 0)$
- **Massless spectrum:**
 - Graviton $g_{\mu\nu}$, dilaton φ and anti-symmetric tensor $B_{\mu\nu}$ in 4D ($\mu = 2, 3$)

$$|q\rangle_R \otimes \alpha_{-1}^\nu |0\rangle_L, \quad \text{with} \quad q = \begin{cases} \pm(1, 0, 0, 0), \\ \pm(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}). \end{cases}$$

- Geometric moduli

$$|q\rangle_R \otimes \alpha_{-1}^{a, \bar{a}} |0\rangle_L, \quad \text{such that} \quad q \cdot v_h \mp v_h^{a, \bar{a}} = 0 \pmod{1},$$

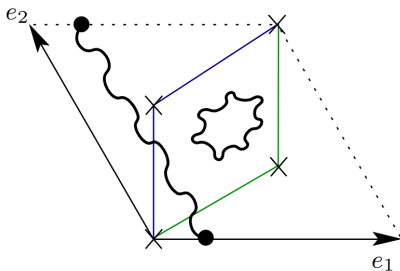
where $a = 1, 2, 3$ denote compact (complex) dimensions and for all $h \in \mathcal{S}$.

Massless spectrum

- Non-twisted sector

$$Z(\tau, \sigma + 2\pi) = Z(\tau, \sigma) + n_\alpha e_\alpha, \quad n_\alpha \in \mathbb{Z}$$

- Graviton, dilaton and antisymmetric tensor
- Gauge bosons
- Geometric moduli
- Charged matter fields



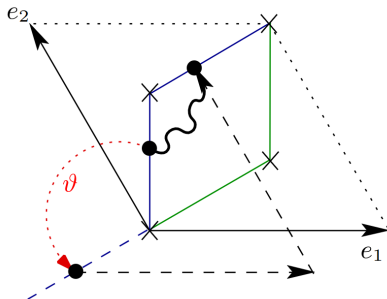
Massless spectrum

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- Twisted sector

- $Z(\tau, \sigma + 2\pi) = \vartheta^k Z(\tau, \sigma) + n_\alpha e_\alpha, \quad k = 1, \dots, N - 1$
- Charged matter fields



- Massless spectrum:

- 16 chargeless gauge bosons

$$|q\rangle_R \otimes \alpha_{-1}^I |0\rangle_L,$$

q as in (8) and $I = 10, \dots, 25$.

- 480 charged gauge bosones

$$|q\rangle_R \otimes |p\rangle_L, \quad \text{with} \quad p^2 = 2,$$

such that $q \cdot v_h = 0 \pmod 1$ (q as in (8)) and $p \cdot V_h = 0 \pmod 1$, then $p \cdot V = 0 \pmod 1$ and $p \cdot A_\alpha = 0 \pmod 1$, $\alpha = 1, \dots, 6$.

- Non-twisted charged matter fields. States as in (10) such that

$$p \cdot V_h - q \cdot v_h = 0 \pmod 1,$$

where q is **not** of the form (8).

$\alpha_{1,2}$ and quadratic indexes

- $g_1 = \sqrt{5/3}g'$, $g_2 = g$ and $g_3 = g_s$
- In the SM the electric charge is $e = g \sin \theta_W = g' \cos \theta_W$, then $\alpha = e^2/(4\pi)$ and so

$$\alpha_1 = \frac{5}{3} \frac{\alpha}{1 - \sin^2 \theta_W} \quad \text{y} \quad \alpha_2 = \frac{\alpha}{\sin^2 \theta_W}.$$

- If T_R^a are the matrices associated to the generators in the rep \mathbf{R} , then

$$\text{Tr}[T_R^a T_R^b] = C(\mathbf{R}) \delta^{ab},$$

where $C(\mathbf{R})$ is the quadratic or Dynkin index. In particular, for the adjoint rep $R = A$, defined by $(T_A^a)^{bc} = -if^{abc}$, where $[T_R^a, T_R^b] = if^{abc} T_R^c$, we have

$$T_A^a T_A^a = C_2(G) \mathbb{1},$$

which defines the quadratic Casimir $C_2(G)$ of the group.

Viable orbifold constructions details

- Negligible kinetic mixing ($10^{-4} - 10^{-2}$)
Goodsell, Ramos, Ringwald [arXiv:1110.6901]
- Accidental global symmetries identified so that fast proton decay is avoided
- At tree level $f_\alpha = S$, then $g_s^{-2} = \langle \text{Re}S \rangle$ at $M_{\text{str}} \approx 10^{17}$ GeV.

Compactification and effective vacua details

- Two point groups \mathbb{Z}_8 -I and \mathbb{Z}_8 -II with $v_I = \frac{1}{8}(1, 2, -3)$ and $v_{II} = \frac{1}{8}(1, 3, -4)$
- 5 inequivalent torus \mathbb{T}^6 geometries: \mathbb{Z}_8 -I $(i, 1)$ with $i = 1, 2, 3$ and \mathbb{Z}_8 -II $(j, 1)$ with $j = 1, 2$
- \mathbb{Z}_8 has the largest fraction of MSSM-like models
Olguin et al. [[arXiv:1808.06622](https://arxiv.org/abs/1808.06622)]
- 138 inequivalent space groups for 17 abelian point groups with $\mathcal{N} = 1$
M. Fischer [[arXiv:hep-th/1209.3906](https://arxiv.org/abs/hep-th/1209.3906)]

Orbifoldo	# modelos tipo MSSM	vacíos efectivos
\mathbb{Z}_8 -I (1,1)	268	1,362
\mathbb{Z}_8 -I (2,1)	246	1,097
\mathbb{Z}_8 -I (3,1)	389	1,989

Orbifoldo	# modelos tipo MSSM	vacíos efectivos
\mathbb{Z}_8 -II (1,1)	2,023	10,023
\mathbb{Z}_8 -II (2,1)	505	2,813

Frequency plots patterns

- Vertical lines: $\alpha_{\text{GUT}} \equiv \alpha_1(M_{\text{GUT}}) = \alpha_2(M_{\text{GUT}})$ implies $(\Lambda_{\text{SUSY}} = \Lambda_{Z'})$

$$\ln \frac{M_{\text{GUT}}}{\Lambda_{Z'}} = 2\pi \frac{\alpha_1^{-1}(\Lambda_{Z'}) - \alpha_2^{-1}(\Lambda_{Z'})}{b_1 - b_2},$$

where only M_{GUT} and $b_1 - b_2$ are model dependent and $b_i \in \mathbb{Q}$.

- Diagonal lines:

$$\alpha_{\text{GUT}}^{-1} = \alpha_2^{-1}(M_{\text{GUT}}) = \alpha_2^{-1}(\Lambda_{Z'}) - \frac{b_2}{2\pi} \ln \frac{M_{\text{GUT}}}{\Lambda_{Z'}},$$

each line describes the RG evolution of the gauge coupling for models with the same b_2 value, points in the line are models with different M_{GUT} .

Stable Higgs vacuum model details

- Model with $\Lambda_{\text{SUSY}} = 10^{12}$ GeV $\approx M_{\text{GUT}}$ from a toroidal orbifold \mathbb{Z}_8 -II (2,1) compactification.
- $V = \frac{1}{4}(-\frac{7}{2}, 0, 0, 0, \frac{1}{2}, \frac{1}{2}, \frac{5}{2}, 3)(-4, -1, 0, 0, 0, \frac{1}{2}, \frac{1}{2}, 3)$
- $A_1 = \frac{1}{4}(1, -7, -7, -5, 2, 2, 1, -3)(-3, 3, -6, -4, 1, -3, 3, 5)$ y
 $A_6 = 0.$
- $t_1 = \frac{1}{4}(1, \frac{5}{3}, \frac{5}{3}, -\frac{5}{3}, 1, 1, 1, 1)(0, 0, 0, 0, 0, 0, 0, 0)$
- $t_4 = \frac{1}{12\sqrt{2}}(-3, 0, 0, 0, 1, 1, 1, -2)(0, 0, 0, 0, 0, 8, 8, 0)$
- $M_{\text{GUT}} \approx 10^{12}$ GeV, $\alpha_{\text{GUT}} \approx 1/32$, $\alpha_4^{-1}(2 \text{ TeV}) \approx 54$
- $b_i = (23/3, -1/3, -19/3, 715/108)$ and
 $b_i^{\text{SUSY}} = (59/5, 5, -2, 731/72)$

Model running and Higgs vacuum stabilization

- RGE initial conditions at $\mu = m_t = 173.1$ GeV (4-loop calculations plus threshold corrections)
Khan et al. [[arXiv:1407.6015](https://arxiv.org/abs/1407.6015)]

$$\sqrt{3/5}g_1 = 0.3587, \quad g_2 = 0.6482, \quad g_3 = 1.1645, \\ h_t = 0.9356 \quad \text{and} \quad \lambda = 0.127$$

- Contributions

$$\Delta\beta(\lambda) \propto g_4^2 Q_\phi'^2 + c g_4^4 Q_\phi'^4, \\ \Delta\beta(h_t) \propto -g_4^2 (Q_q'^2 + Q_t'^2) h_t,$$

increase the value of λ and lower h_t . The running of g_4 depends on the exotics, which modifies this contributions.

RGEs used by SARAH

Higgs quartic coupling beta function

$$\beta(\lambda) \equiv \frac{\partial \lambda}{\partial \ln \mu} = \frac{1}{(4\pi)^2} \left[24\lambda^2 - \lambda \left(\frac{9}{5}g_1^2 + 9g_2^2 \right) + \frac{9}{8} \left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2g_2^2 + g_2^4 \right) + 4\lambda Y_2(S) - 2H(S) \right],$$

where

$$Y_2(S) \equiv \text{Tr} \left[3h_u^\dagger h_u + 3h_d^\dagger h_d + h_e^\dagger h_e \right],$$

$$H(S) \equiv \text{Tr} \left[3(h_u^\dagger h_u)^2 + 3(h_d^\dagger h_d)^2 + (h_e^\dagger h_e)^2 \right],$$

the matrices in family space h_u, h_d and h_e are the Yukawa couplings, whose RGEs are

$$h_u^{-1} \frac{\partial h_u}{\partial \ln \mu} = \frac{1}{(4\pi)^2} \left[\frac{3}{2} \left(h_u^\dagger h_u - h_d^\dagger h_d \right) + Y_2(S) - \left(\frac{17}{20}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2 \right) \right],$$

$$h_d^{-1} \frac{\partial h_d}{\partial \ln \mu} = \frac{1}{(4\pi)^2} \left[\frac{3}{2} \left(h_d^\dagger h_d - h_u^\dagger h_u \right) + Y_2(S) - \left(\frac{1}{4}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2 \right) \right],$$

$$h_e^{-1} \frac{\partial h_e}{\partial \ln \mu} = \frac{1}{(4\pi)^2} \left[\frac{3}{2} h_e^\dagger h_e + Y_2(S) - \frac{9}{4} (g_1^2 + g_2^2) \right].$$

Mass generation

Dominant contributions to the mass terms (effective Lagrangian)

$$\mathcal{L} \supset -h_{33}^u \bar{u}_3 \tilde{\phi}_u^\dagger q_3 - h_{11,22}^u \bar{u}_{1,2} \tilde{\phi}_u^\dagger q_{1,2} s_2^2 - h_{33}^d \bar{d}_3 \tilde{\phi}_d^\dagger q_3 s_1^7 s_2^2 - h_{11,22}^d \bar{d}_{1,2} \tilde{\phi}_d^\dagger q_{1,2} s_2^2 \\ - h_{33}^e \bar{e}_3 \tilde{\phi}_d^\dagger \ell_3 s_1^2 - h_{11,22}^e \bar{e}_{1,2} \tilde{\phi}_d^\dagger \ell_{1,2} s_2^2 - h_{ii}^\nu N_i^b \tilde{\phi}_u^\dagger \ell_3 s_2^2 - k_{ij} N_i^a N_j^c s_1 + \text{h.c.},$$

where $\tilde{\phi}_{u,d}$ are the \mathcal{CP} conjugate doublets. By choosing, for example $\langle s_1 \rangle \sim \mathcal{O}(10)$, $\langle s_2 \rangle \sim \mathcal{O}(10^{-5})$ and $\langle \phi_d \rangle \sim \mathcal{O}(10^{-4}) \langle \phi_u \rangle$ the correct hierarchies $m_t/m_u \approx 10^5$, $m_t/m_b \approx 10^2$ and $m_t/m_\tau \approx 10^2$ are obtained if $h^{u,d,e}$ are of order one.

Stringy THDM details

- $\mathbb{Z}_2 \times \mathbb{Z}_4$ (2,4) toroidal orbifold compactification
- $V_1 = \frac{1}{4}(-5, -1, 1, 1, 1, 1, 1, 1)(-7, -7, -1, -1, -1, -1, 1, 1)$
 $V_2 = \frac{1}{8}(5, -3, -7, -1, -1, 1, 1, 5)(-7, -3, -1, 1, 1, 7, -7, 5)$
- $A_1 = A_2 = 0,$
 $A_3 = A_4 = A_6 = \frac{1}{4}(-7, 5, 5, 3, 3, -3, 1, 5)(1, 1, 7, 1, 3, 5, 9, 9),$
 $A_5 = (0, 0, 0, 0, 0, 0, 0, 0)(0, 1, -2, 1, 1, 1, 2, -2)$

5 Backup slides

6 Gauge coupling of $U(1)'$ models

Work done at UNAM:

- $U(1)'$ *coupling constant at low energies from heterotic orbifolds*, Yessenia Olguin-Trejo, O. P.-F., Ricardo Perez-Martinez y Saul Ramos-Sanchez, Phys. Lett. B **795** (2019) 673-681.
arXiv:1901.10102 [hep-ph].



Scenario

- Heterotic string $E_8 \times E_8$
in toroidal orbifold \mathbb{Z}_8 with $\mathcal{N} = 1$ in 4D
- $\mathcal{G}_{4D} = \mathcal{G}_{SM} \times [U(1)']^n \times \mathcal{G}_{\text{hidden}}$ ($n \leq 10$)
 - SM singlets break it into $\mathcal{G}_{\text{eff}} = \mathcal{G}_{SM} \times U(1)' \subset \mathcal{G}_{4D}$
(Z' model known to stabilize the Higgs vacuum with few exotics [Di Chiara et al. \[arXiv:1412.7036\]](#))
- Massless spectrum: **MSSM + vectorial exotics**

RGEs

- 1-loop gauge couplings RGEs

$$\beta(g_i) \equiv \frac{\partial g_i}{\partial \ln \mu} = \frac{b_i g_i^3}{(4\pi)^2} \quad \Rightarrow \quad \frac{\partial \alpha_i^{-1}}{\partial \ln \mu} = -\frac{b_i}{2\pi},$$

where $\alpha_i = g_i^2/(4\pi)$ and $i = 1, 2, 3$

- Solution

$$\alpha_i^{-1}(\mu) = \alpha_i^{-1}(\mu_0) - \frac{b_i}{2\pi} \ln \left(\frac{\mu}{\mu_0} \right).$$

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- b coefficients

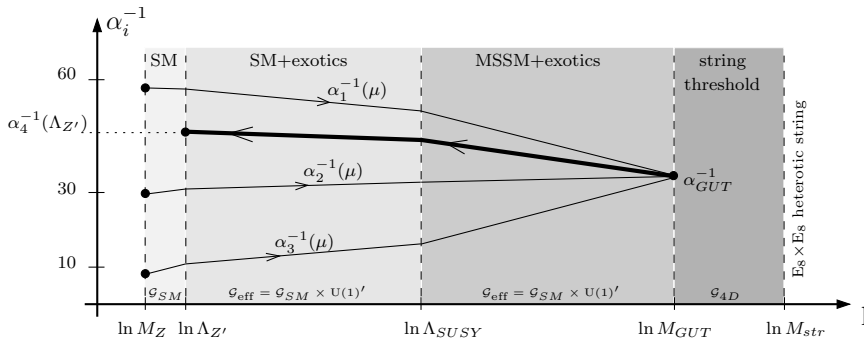
$$b_i = -\frac{11}{3}C_2(G_i) + \frac{2}{3} \sum_f n_f C(\mathbf{R}_f) + \frac{1}{3} \sum_s n_s C(\mathbf{R}_s),$$

so $(b_1, b_2, b_3) = \left(\frac{41}{10}, -\frac{19}{6}, -7\right)$, and with SUSY

$$b_i^{\text{SUSY}} = -3C_2(G_i) + \sum_{\Phi} n_{\Phi} C(\mathbf{R}_{\Phi}),$$

then $(b_1, b_2, b_3)^{\text{SUSY}} = \left(\frac{33}{5}, 1, -3\right)$.

Coupling evolution (running)

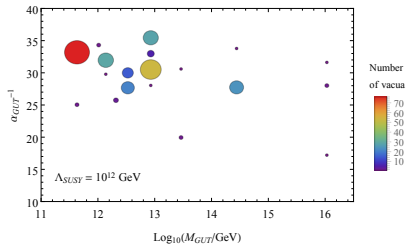
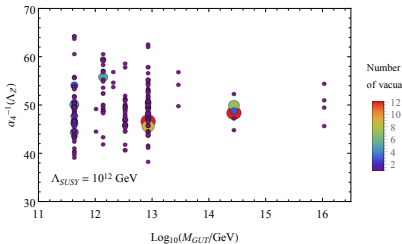
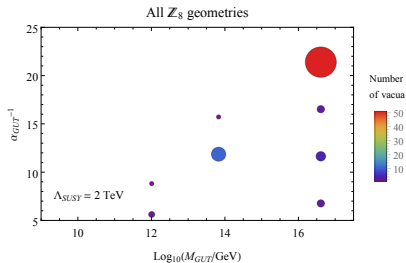
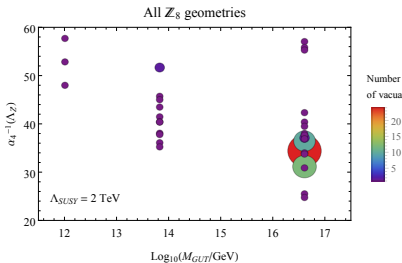


$$\mathcal{G}_{4D} = \mathcal{G}_{SM} \times [U(1)']^n \times \mathcal{G}_{hidden}$$

Results

~ 17,000 effective vacua and 0.5 – 1.5% with gauge coupling unification

- Low Λ_{SUSY} (2 TeV)
 - $25 \leq \alpha_4^{-1}(\Lambda_{Z'}) \leq 60 \rightarrow 0.46 \leq g_4(\Lambda_{Z'}) \leq 0.7$
 - $M_{\text{GUT}} \in \{10^{12} \text{ GeV}, 6.6 \times 10^{13} \text{ GeV}, 4.1 \times 10^{16} \text{ GeV}\}$
 - $5.6 \leq \alpha_{\text{GUT}}^{-1} \leq 21.4$ most frequent: $\alpha_{\text{GUT}} \approx 1/21 \sim 1/25$ and $g_4(2 \text{ TeV}) \approx 0.6 \lesssim g_2$
- Intermediate and High Λ_{SUSY} ($10^{12}, 10^{17} \text{ GeV}$)
 - $38 \leq \alpha_4^{-1}(\Lambda_{Z'}) \leq 64 \rightarrow 0.44 \leq g_4(\Lambda_{Z'}) \leq 0.6$
 - $4.3 \times 10^{11} \text{ GeV} \leq M_{\text{GUT}} \leq 10^{16} \text{ GeV}, g_4(\Lambda_{Z'}) \approx 0.5$
 - $17 \leq \alpha_{\text{GUT}}^{-1} \leq 36$ most frequent: $M_{\text{GUT}} \approx 4.3 \times 10^{11} \text{ GeV}, \alpha_{\text{GUT}} \approx 1/33$



A model with Higgs vacuum stabilization

- 1-loop RGEs with SARAH [F. Staub \[arXiv:1309.7223\]](#)
- type-I seesaw mechanism
- Some fine-tuning for correct mass hierarchies (except e , d)
- Residual flavor symmetry (1st and 2nd gens)
- Arbitrary choice of f and s reps introduces spurious anomalies

Conclusions

- \mathbb{Z}_8 toroidal orbifold compactifications of the heterotic string lead to effective vacua which are $U(1)'$ models with the MSSM particle spectrum and some extra exotics. Demanding
 - coupling unification
 - specific SUSY and $U(1)'$ breaking scaleswe restrict to 0.5 – 1.5% of them and constrain the extra Abelian coupling to $0.44 < g_4(2\text{TeV}) < 0.7$.
- We looked into a particular model with Higgs vacuum stabilization and argued that it has promising characteristics, which can be generic to the effective vacua.