BSM phenomenology from heterotic string orbifolds

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4. Phenomenology of orbifold compactifications
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   - Higgs-portal DM
5. Conclusions

Content

SM irreps

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

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

V_μ	irrep
G^a_μ	$(\mathbf{8},\mathbf{1})_0$
W^a_μ	$(\mathbf{1},\mathbf{3})_0$
B_μ	$(\mathbf{1},\mathbf{1})_0$

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

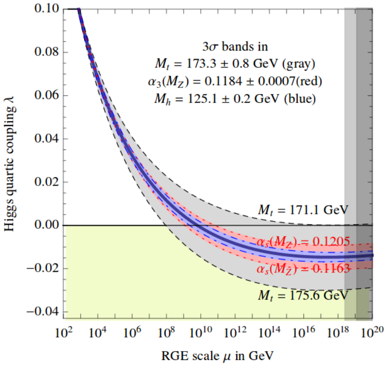
Beyond the SM

- 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)
  - Dark energy
- Naturalness and hierarchy problems:
  - Mass hierarchy
  - Electroweak hierarchy problem
  - Strong CP problem

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

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

Content

Bottom-up

- Z' models : extra $\mathrm{U}(1)'$ symmetry,
  - Exotics required to avoid gauge anomalies
  - Can be motivated from GUTs like E_6
  - Known to stabilize the Higgs vacuum in the presence of few exotics charged under the $\mathrm{U}(1)'$
    Di Chiara et al. [arXiv:1412.7036]
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  - Detection limits $m_{Z'} \gtrsim 2\,$TeV (2018)
- Higgs portal models : Higgs coupled to dark sector
  - THDM extensively studied
  - Higgs portals to a singlet DM candidate are prolific scenarios

Top-down

- SUSY
  - $N_f = N_b$

Φ	s	f	irrep
Q	$\tilde{q}$	q	$(\mathbf{3},\mathbf{2})_{1/6}$
L	$\tilde{\ell}$	ℓ	$(\mathbf{1},\mathbf{2})_{-1/2}$
$\overline{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}},\mathbf{1})_{-2/3}$
$\overline{d}$	$\tilde{u}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$
$\overline{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1},\mathbf{1})_{1}$
H_u	ϕ_u	$\tilde{\phi}_u$	$(\mathbf{1},\mathbf{2})_{1/2}$
H_d	ϕ_d	$\tilde{\phi}_d$	$(\mathbf{1},\mathbf{2})_{-1/2}$

V	f	V_μ	irrep
G^a	$\tilde{G}^a$	G_μ^a	$(\mathbf{8},\mathbf{1})_0$
W^a	$\tilde{W}^a$	W_μ^a	$(\mathbf{1},\mathbf{3})_0$
B	$\tilde{B}$	B_μ	$(\mathbf{1},\mathbf{1})_0$

MSSM spectrum

Top-down

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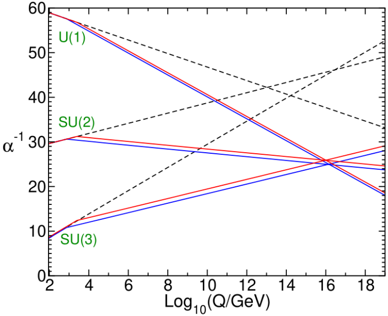

S. P. Martin [arXiv:9709356]

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- String theory

Content

Action and Symmetries

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

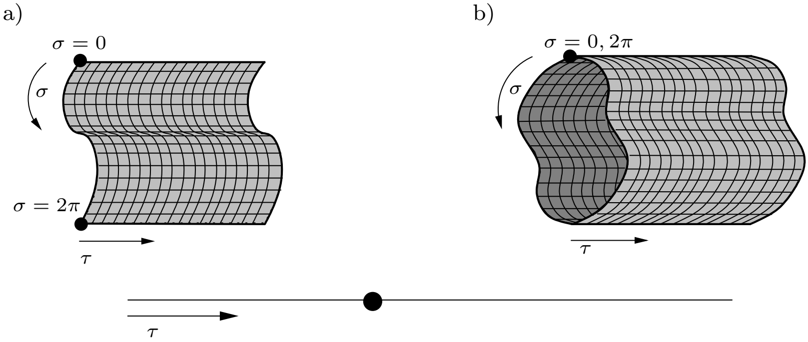

Figure: Worldsheets of an a) open and a b) closed string in comparison with a particle's worldline (down).

Action and Symmetries

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- Nambu-Goto action (worldsheet area) non-polinomial $\rightarrow$ Polyakov action via worldsheet metric

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

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

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- Symmetries...
  - Spacetime reparams (diffeos) $x^M \rightarrow \overline{x}^M(x)$ then $X^M(\tau,\sigma) \rightarrow \overline{X}^M(\tau,\sigma) = \overline{x}(X(\tau,\sigma))$
  - Worldsheet reparametrizations $\sigma^a \rightarrow \overline{\sigma}^a(\sigma)$
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- Even after fixing some gauge freedom there is a remaining conformal symmetry $\rightarrow$ CFT

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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- String excitations (oscillation modes in spacetime) are particles of a QFT at low energy

Quantization and interactions

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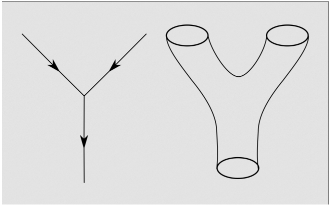

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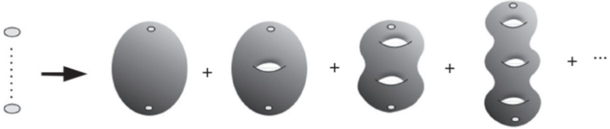
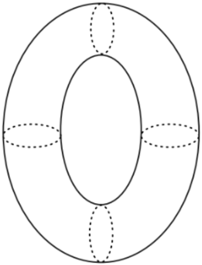
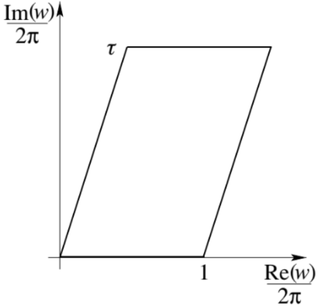


- Gauge freedom $\leftrightarrow$ modular invariance of the string amplitudes





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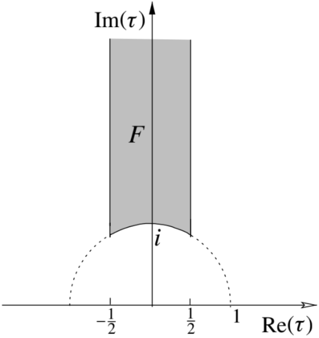

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  Conformal invariance in the worldsheet
  $\longleftrightarrow$ String dynamics in spacetime

Superstring Theories

- Only bosons in the spectrum → SUSY
  - Add $\Psi^M(\tau,\sigma)$ spinors in the worldsheet but vectors in spacetime
  - Periodic (R) or antiperiodic (NS) conditions $\Psi^M(\tau,\sigma+2\pi)=\pm\Psi^M(\tau,\sigma)$
  - Now $D=10$ for the Weyl anomaly to disappear

Superstring Theories

- Only bosons in the spectrum → SUSY
- Modular invariance (of the partition function up to 1 loop) allows to define:
  - $\mathcal{N} = 2$ theories IIA and IIB,
  - $\mathcal{N} = 1$ theory I with gauge group $\mathrm{SO}(32)$ to cancel anomalies and two heterotic $\mathrm{SO}(32)$ and $\mathrm{E}_8 \times \mathrm{E}_8$
  - $\mathcal{N} = 0$ heterotic with $\mathrm{SO}(16) \times \mathrm{SO}(16)$ gauge group

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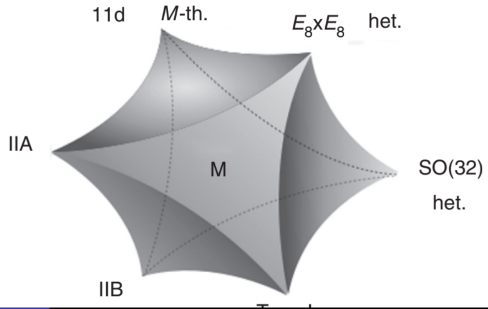
- Several superstring theories → M theory unification (dualities)



Advantages:

- Unification, quantum description of gravity (Einstein in the low energy limit)
- No UV divergences
- Can obtain the SM gauge group, for example by branes which allow a geometric mechanism for symmetry breaking (type IIB)
- Low energy limit is a QFT

Disadvantages/issues:

- $D = 26$ or $D = 10$ for the superstring models
- No realistic model yet
- SUSY breaking mechanism
- Moduli stabilization

Content

Generalities

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

- Heterotic string $\mathsf{E}_8 \times \mathsf{E}_8$, $p = (p^I) \in \Lambda_{\mathsf{E}_8 \times \mathsf{E}_8}$.

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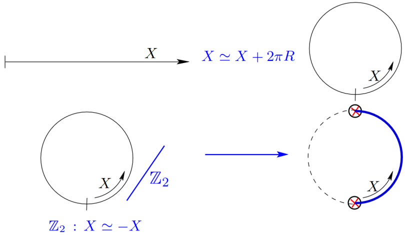

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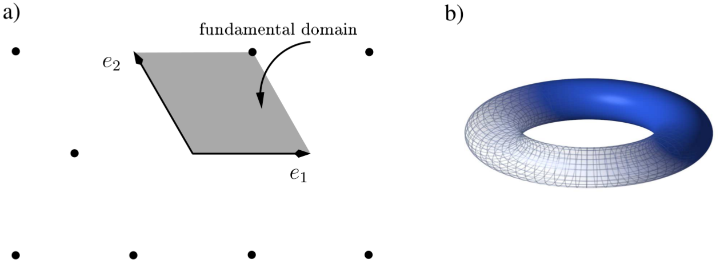
- Compactify in a toroidal orbifold $\mathcal{O}$
  - $\Gamma = \{n_\alpha e_\alpha | n_\alpha \in \mathbb{Z}, \alpha = 1, \ldots, 6\}$ genera $\mathbb{T}^6$
  - Toda $\theta \in \mathcal{P}$ cumple $\theta e_\alpha \in \Gamma$
  - Grupo de espacio $\mathcal{S} = \mathcal{P} \ltimes \Gamma$, $g = (\theta, n_\alpha e_\alpha) \in \mathcal{S}$
  - Identificación $X \sim \theta X + n_\alpha e_\alpha$ con $\theta = \vartheta^k \in \mathcal{P} = \mathbb{Z}_N$, $k \in \mathbb{Z}$
  - En coordenadas complejas $\vartheta = \text{diag}(e^{2\pi i v^1}, e^{2\pi i v^2}, e^{2\pi i v^3})$ y se denota $v = (0, v^1, v^2, v^3)$

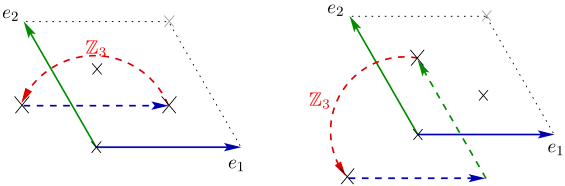
2D Torus



[1]

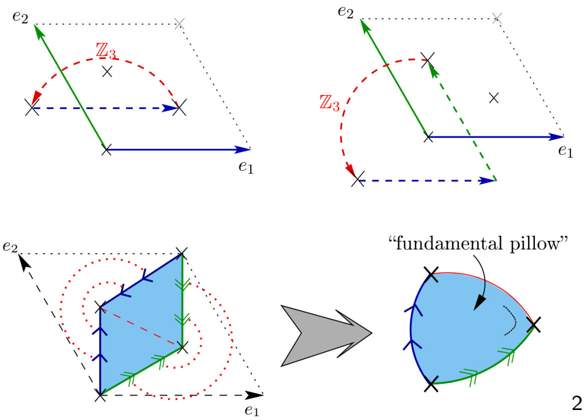
[1] Ramos, stringpheno.fisica.unam.mx

$\mathbb{Z}_3$ orbifold in 2D



[2] Ramos, stringpheno.fisica.unam.mx

$\mathbb{Z}_3$ orbifold in 2D



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Constraints

- The orbifold action is embedded in the gauge group degrees of freedom in the form of the group $\mathcal{G}$.
  - $\mathcal{S} \hookrightarrow \mathcal{G}$ such that $g = (\vartheta^k, n_\alpha e_\alpha) \longmapsto (kV, n_\alpha A_\alpha)$, with $k, n_\alpha \in \mathbb{Z}$
  - $X^I \to X^I + kV^I + n_\alpha A^I_\alpha$, $I = 10, \dots, 25$ with $NV, NA_\alpha \in \Lambda$
  - WL: gauge transformations associated to non-contractible loops in each direction e_α of the torus

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  - WL: gauge transformations associated to non-contractible loops in each direction e_α of the torus
- Supersymmetry and modular invariance
  - SUSY $\mathcal{N} = 1$ in 4D, holonomy SU$(3) \supset \mathcal{P}$ then $v^1 + v^2 + v^3 = 0$
  - Modular invariance of the 1-loop partition function implies

$$\begin{aligned} N(V^2 - v^2) &= 0 \quad \text{mod } 2, \\ N_\alpha(A_\alpha \cdot V) &= 0 \quad \text{mod } 2, \\ N_\alpha(A_\alpha^2) &= 0 \quad \text{mod } 2, \\ \text{gcd}(N_\alpha, N_\beta)(A_\alpha \cdot A_\beta) &= 0 \quad \text{mod } 2 \ (\alpha \neq \beta), \end{aligned}$$

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

Massless spectrum

- Right movers
  - States $\psi^M_{-1/2}|0\rangle_R$ in NS sector and $\psi^M_0|0\rangle_R$ in R ($M = 2, \ldots, 9$) are $|q\rangle_R$ where q denotes the weight of the SO(8) rep

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

  - For massless states

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

- Left movers
  - States $\alpha^M_{-1}|0\rangle_L$, $\alpha^I_{-1}|0\rangle_L$ with $I = 10, \ldots, 25$ or $|p\rangle_L$ where $p^2 = 2$.
  - Massless states

$$\frac{\alpha' m_L^2}{4} = \frac{1}{2}p^2 + N - 1 = 0, \quad \text{where} \quad N = \sum_{n>0}(\alpha^M_{-n}\alpha^M_n + \alpha^I_{-n}\alpha^I_n).$$

Orbifold projection

Compatibility of the orbifold action with the Hilbert space

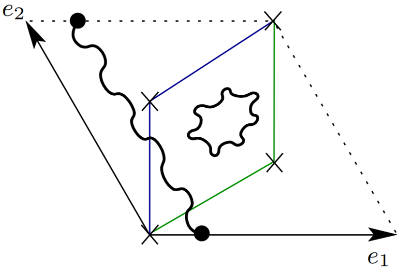
- In $\mathcal{H}_g$ the states satisfy $Z(\tau, \sigma + 2\pi) = gZ(\tau, \sigma)$, $g \in \mathcal{S}$
- If $h \in \mathcal{Z}_g \equiv \{h \in \mathcal{S} | [g, h] = 0\}$ then hZ defines the same state
- The action

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

implies the constraint $\varphi = 0 \bmod 1$.

Non-twisted sector

- $Z(\tau, \sigma + 2\pi) = Z(\tau, \sigma) + n_\alpha e_\alpha, \quad n_\alpha \in \mathbb{Z}$.
- States $|q\rangle_R \otimes \alpha^x_{-1}|p\rangle_L$ $(x = M, I)$ associated to $g = (\mathbb{1}, 0)$.
- $\varphi = p \cdot V_h - q \cdot v_h + (\delta_{x,a} - \delta_{x,\bar{a}})v_h^{a,\bar{a}}$, $h \in \mathcal{S}$.
- Massless spectrum: Graviton, dilaton, anti-symmetric tensor, geometric moduli, gauge bosons and charged matter fields.



Twisted sector

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

Twisted sector

- $Z(\tau, \sigma + 2\pi) = \vartheta^k Z(\tau, \sigma) + n_\alpha e_\alpha$, $k = 1, \ldots, N-1$.
- 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 $V_g = kV + n_\alpha A_\alpha$
- α denotes $\alpha^a_{-\eta^a}$ and $\alpha^{\bar{a}}_{-1+\eta^a}$ products
  where $\eta^a = kv^a$ mod 1 $(0 < \eta^a \leq 1)$

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

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  with $v_g = kv$ and $V_g = kV + n_\alpha A_\alpha$
- 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 $N = \sum_{a=1}^3 \eta^a (N_g^a + N_g^{*\bar{a}})$

Twisted sector

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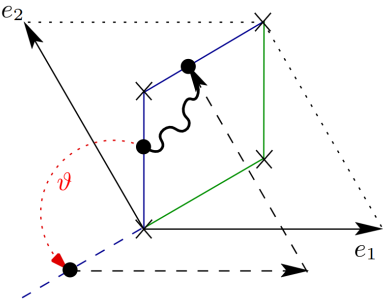

Content

Content

Work done at UNAM:

- $\mathrm{U}(1)'$ *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 $\mathrm{E}_8 \times \mathrm{E}_8$ in toroidal orbifold $\mathbb{Z}_8$ with $\mathcal{N} = 1$ in 4D
- `orbifolder` to calculate the massless spectrum
  Nilles et al. [arXiv:1110.5229]
  - Modular invariance and WL constraints
- $\mathcal{G}_{4\text{D}} = \mathcal{G}_{\text{SM}} \times [\mathrm{U}(1)']^n \times \mathcal{G}_{\text{hidden}}$ $(n \leq 10)$
  - SM singlets break to $\mathcal{G}_{\text{eff}} = \mathcal{G}_{\text{SM}} \times \mathrm{U}(1)' \subset \mathcal{G}_{4\text{D}}$
- Massless spectrum: MSSM + vectorial exotics

Effective vacua

- One-loop RGEs with
  - Gauge coupling unification
  - $\Lambda_{Z'} = 2$ TeV threshold scale for $\mathrm{U}(1)'$ breaking
  - SUSY breaking at $\Lambda_{\text{SUSY}} \geq \Lambda_{Z'}$
    - $\Lambda_{\text{SUSY}} = \Lambda_{Z'} = 2$ TeV
    - $\Lambda_{\text{SUSY}} = 10^{12}$ GeV
    - $\Lambda_{\text{SUSY}} = M_{\text{str}} = 10^{17}$ GeV

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- Further constraints:
  - $b_4 \neq 0$ or the coupling to the Z' is suppressed (spectrum charged under $\mathrm{U}(1)'$)
  - $m_Z < M_{\mathsf{GUT}} < M_{\mathsf{str}}$
  - $0 < \alpha_i < 1$, rather $g_i < 1$ (difference of ∼10 models)

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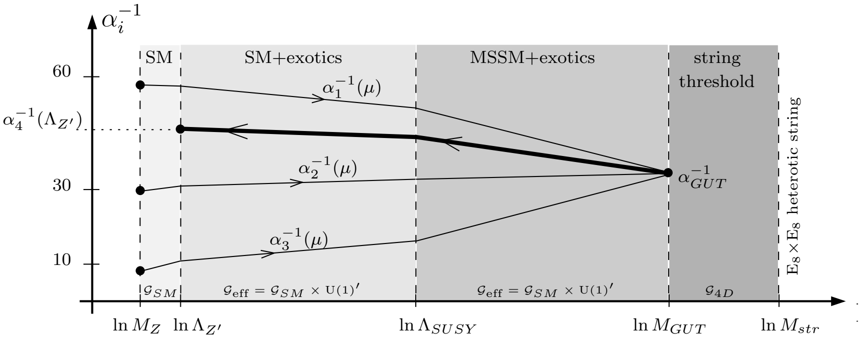
  - $0 < \alpha_i < 1$, rather $g_i < 1$ (difference of ∼10 models)
- Unification criteria
  - $\alpha_1 = \alpha_2$ defines α_{GUT} and M_{GUT}
  - $|\alpha_{\mathsf{GUT}}^{-1} - \alpha_3^{-1}(M_{\mathsf{GUT}})| < 0.26$ (3σ interval of $\alpha_3(m_Z)$)

Coupling evolution (running)



$$\mathcal{G}_{\text{4D}} = \mathcal{G}_{\text{SM}} \times [\mathrm{U}(1)']^n \times \mathcal{G}_{\text{hidden}}$$
$$\mathcal{G}_{\text{SM}} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

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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- Solution

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

- 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

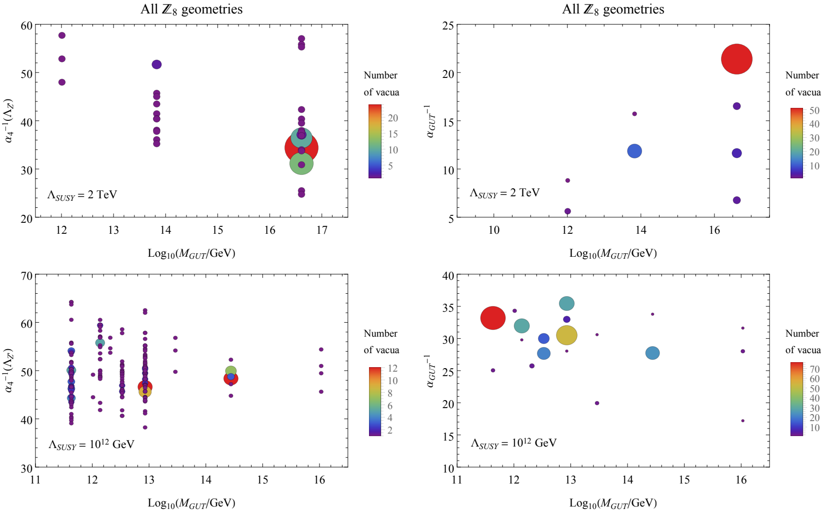
$$b_i^{\text{SUSY}} = -3C_2(G_i) + \sum_\Phi n_\Phi C(\mathbf{R}_\Phi)\,,$$

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

Results

$\sim 17,000$ 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} GeV)
  - $38 \leq \alpha_4^{-1}(\Lambda_{Z'}) \leq 64 \rightarrow 0.44 \leq g_4(\Lambda_{Z'}) \leq 0.6$
  - $4.3 \times 10^{11}\text{GeV} \leq M_{\text{GUT}} \leq 10^{16}\text{GeV}$, $\overline{g_4(\Lambda_{Z'})} \approx 0.5$
  - $17 \leq \alpha_{\text{GUT}}^{-1} \leq 36$ most frequent: $M_{\text{GUT}} \approx 4.3 \times 10^{11}\text{GeV}$, $\alpha_{\text{GUT}} \approx 1/33$



All $\mathbb{Z}_8$ geometries
$\alpha_4^{-1}(\Lambda_Z)$
$\Lambda_{SUSY} = 2$ TeV
$\text{Log}_{10}(M_{GUT}/\text{GeV})$
Number of vacua
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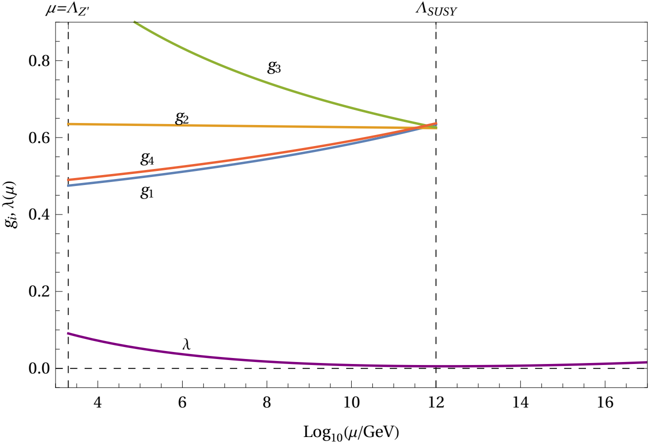
A model with Higgs vacuum stabilization

- 1-loop RGEs with SARAH F. Staub [arXiv:1309.7223]



A model with Higgs vacuum stabilization

- 1-loop RGEs with SARAH F. Staub [arXiv:1309.7223]
- type-I seesaw mechanism

#	irrep	f
2	$(\mathbf{1},\mathbf{2})_{(-1/2,\,-7/12\sqrt{2})}$	$\ell_{1,2}$
1	$(\mathbf{1},\mathbf{2})_{(-1/2,\,1/3\sqrt{2})}$	ℓ_3
2	$(\mathbf{1},\mathbf{1})_{(1,\,-1/6\sqrt{2})}$	$\bar{e}_{1,2}$
1	$(\mathbf{1},\mathbf{1})_{(1,\,1/12\sqrt{2})}$	$\bar{e}_3$
2	$(\mathbf{3},\mathbf{2})_{(1/6,\,-1/6\sqrt{2})}$	$q_{1,2}$
1	$(\mathbf{3},\mathbf{2})_{(1/6,\,1/4\sqrt{2})}$	q_3
2	$(\bar{\mathbf{3}},\mathbf{1})_{(-2/3,\,-1/6\sqrt{2})}$	$\bar{u}_{1,2}$
1	$(\bar{\mathbf{3}},\mathbf{1})_{(-2/3,\,1/12\sqrt{2})}$	$\bar{u}_3$
2	$(\bar{\mathbf{3}},\mathbf{1})_{(1/3,\,-7/12\sqrt{2})}$	$\bar{d}_{1,2}$
1	$(\bar{\mathbf{3}},\mathbf{1})_{(1/3,\,3/4\sqrt{2})}$	$\bar{d}_3$

#	irrep	f
1	$(\bar{\mathbf{3}},\mathbf{1})_{(1/3,\,3/4\sqrt{2})}$	$\bar{x}_i$
1	$(\mathbf{3},\mathbf{1})_{(-1/3,\,1/12\sqrt{2})}$	x_i
8	$(\mathbf{1},\mathbf{2})_{(0,\,1/6\sqrt{2})}$	η_i
8	$(\mathbf{1},\mathbf{1})_{(1/2,\,1/6\sqrt{2})}$	ζ_i
8	$(\mathbf{1},\mathbf{1})_{(-1/2,\,7/12\sqrt{2})}$	$\bar{\zeta}_i$
8	$(\mathbf{1},\mathbf{1})_{(-1/2,\,-1/12\sqrt{2})}$	$\bar{\kappa}_i$
8	$(\mathbf{1},\mathbf{1})_{(1/2,\,-1/6\sqrt{2})}$	κ_i
11	$(\mathbf{1},\mathbf{1})_{(0,\,1/3\sqrt{2})}$	N_i^a
10	$(\mathbf{1},\mathbf{1})_{(0,\,-2/3\sqrt{2})}$	N_i^b
8	$(\mathbf{1},\mathbf{1})_{(0,\,-1/12\sqrt{2})}$	N_i^c
6	$(\mathbf{1},\mathbf{1})_{(0,\,-5/12\sqrt{2})}$	N_i^d
4	$(\mathbf{1},\mathbf{1})_{(0,\,7/12\sqrt{2})}$	N_i^e
2	$(\mathbf{1},\mathbf{1})_{(0,\,-1/4\sqrt{2})}$	N_i^f

#	irrep	s
1	$(\mathbf{1},\mathbf{2})_{(1/2,\,-1/3\sqrt{2})}$	ϕ_u
1	$(\mathbf{1},\mathbf{2})_{(-1/2,\,1/12\sqrt{2})}$	ϕ_d
1	$(\mathbf{1},\mathbf{1})_{(0,\,-1/4\sqrt{2})}$	s_1
1	$(\mathbf{1},\mathbf{1})_{(0,\,1/3\sqrt{2})}$	s_2

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

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
- SUSY and flavor symmetry breaking analysis needed

Content

- *Higgs-portal darl 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 $\mathrm{SO}(16) \times \mathrm{SO}(16)$ in toroidal orbifold $\mathbb{Z}_2 \times \mathbb{Z}_4(2,4)$ (fruitful)
- $\mathcal{G}_{\text{4D}} = \mathcal{G}_{\text{SM}} \times \mathcal{G}' \times [\mathrm{U}(1)']^8$ 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
- freeze-out drives DM production
    - 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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- freeze-out drives DM production
  - DM particle out of thermal equilibrium when the expansion of the Universe is faster than the interaction rate for the processes DM$\longleftrightarrow$SM
- 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

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

#	Fermionic irrep.	Label
3	$(\mathbf{1},\mathbf{2};\mathbf{1})_{-1/2}$	$\ell_{\text{L},i}$
1	$(\mathbf{1},\mathbf{1};\mathbf{2})_{1}$	$\bar{e}_{\text{L}}$
1	$(\mathbf{1},\mathbf{1};\mathbf{1})_{1}$	$\bar{e}_{\text{L},3}$
1	$(\mathbf{3},\mathbf{2};\mathbf{2})_{1/6}$	q_{L}
1	$(\mathbf{3},\mathbf{2};\mathbf{1})_{1/6}$	$q_{\text{L},3}$
1	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{2})_{-2/3}$	$\bar{u}_{\text{L}}$
1	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1})_{-2/3}$	$\bar{u}_{\text{L},3}$
5	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1})_{1/3}$	$\bar{d}_{\text{L},i}$
2	$(\mathbf{3},\mathbf{1};\mathbf{1})_{-1/3}$	$d'_{\text{L},i}$
131	$(\mathbf{1},\mathbf{1};\mathbf{1})_{0}$	$\nu_{\text{R},i}$
14	$(\mathbf{1},\mathbf{1};\overline{\mathbf{2}})_{0}$	$\nu'_{\text{R},i}$

#	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	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{2})_{1/3}$	x_i

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

- At tree level:
  - masses for extra $d'_{\mathsf{L},i}$
  - Yukawa couplings such that the heaviest quarks and lepton can be identified
  - Leptoquark x_i interactions
  - Potential: Higgs + Singlet DM candidate + Interaction

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

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

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

- Upon EWSB

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

$$\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \longrightarrow \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \sigma_2) \end{pmatrix}$$

- 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]

$$\begin{aligned} m_h &= 125.25(17)\,\text{GeV}\,, \\ v &= 246.219640(63)\,\text{GeV}\,, \\ \Omega_{\text{DM}}h^2 &= 0.120(1)\,, \end{aligned}$$

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

- Parameters

$$\begin{aligned} &\mu_{12}^2,\ \tan\beta = v_2/v_1,\ \lambda_i, \qquad\qquad (i = 1,\ldots,7) \\ &\mu_S^2,\ \lambda_S,\ \lambda_{1S},\ \lambda_{2S},\ \lambda_{12S} \end{aligned}$$

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. lmfit/lmfit-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 $\rightarrow \chi^2 = 1.23 \times 10^{-4}$

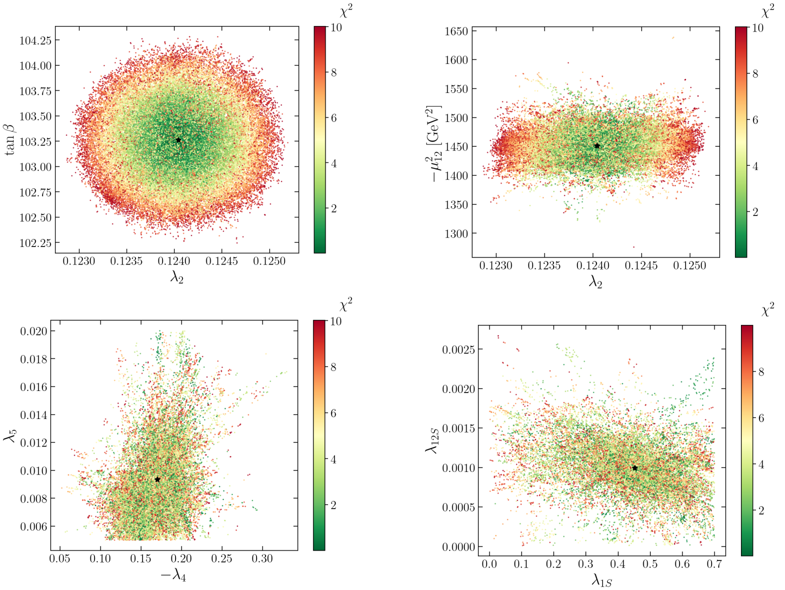
Results

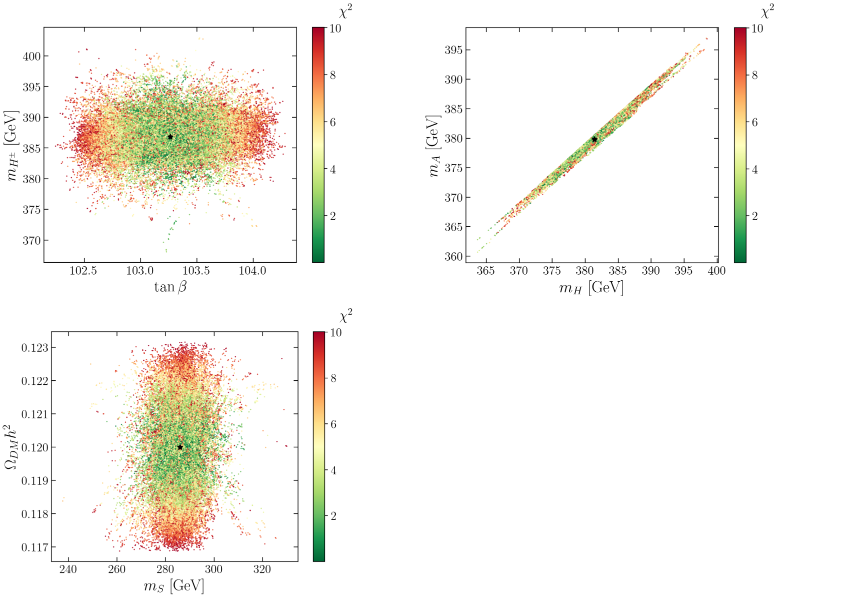
Higgs parameter	value
λ_1	3.63×10^{-4}
λ_2	1.24×10^{-1}
λ_3	5.03×10^{-1}
λ_4	-1.7×10^{-1}
λ_5	9.35×10^{-3}
λ_6	5.52×10^{-4}
λ_7	3.76×10^{-4}
μ_{12}^2	$-1.45 \times 10^3\,\mathrm{GeV}^2$
v_1	$2.394\,\mathrm{GeV}$
v_2	$246.21\,\mathrm{GeV}$

Higgs-portal parameter	value
μ_S^2	$7.77 \times 10^4\,\mathrm{GeV}^2$
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	$125.25\,\mathrm{GeV}$
m_H	$381.41\,\mathrm{GeV}$
$m_{H^\pm}$	$386.82\,\mathrm{GeV}$
m_A	$379.82\,\mathrm{GeV}$
$\Omega_{\mathrm{DM}}h^2$	0.12
m_S	$286.01\,\mathrm{GeV}$
χ^2	1.23×10^{-4}

- $\tan\beta = 102.84$


$\tan\beta$
λ_2
χ^2
$-\mu_{12}^2$ [GeV^2]
λ_2
χ^2
λ_5
$-\lambda_4$
χ^2
λ_{12S}
λ_{1S}
χ^2


χ^2
$m_{H^\pm}$ [GeV]
$\tan\beta$
m_A [GeV]
m_H [GeV]
$\Omega_{DM}h^2$
m_S [GeV]

Content

- 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 that nature is described by it.
- Low energy models originating in string compactifications may possess the correct ingredients to solve SM extant problems, such as Higgs stabilization, DM particle description, neutrino mass generation, experimental anomalies.
- Heterotic orbifolds are rich scenarios where interesting pheno can be found.
- We explored the realization of $\mathrm{U}(1)'$ models at low energy from the toroidal orbifold $\mathbb{Z}_8$ compactifications and obtained the massless spectrum of MSSM-like models with extra exotics.

- With reasonable assumptions such as coupling unification and specific SUSY and $\mathrm{U}(1)'$ breaking scales, we found limits for the extra Abelian coupling keeping $0.5 - 1.5\%$ of the effective vacua. We constrained $0.44 < g_4(2\text{TeV}) < 0.7$.
- We looked into a particular model in with Higgs vacuum stabilization and argued that it has promising characteristics, which can be generic to the effective vacua.
- We explored vacua from the non-supersymmetric heterotic string compactified in an abelian toroidal orbifold with point group $\mathbb{Z}_2 \times \mathbb{Z}_4$. A parameter scan for a particular realization of the THDM shows that the correct DM relic abundance can be obtained for 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 pheno that is left to be researched.

Thanks!

Thanks!

Questions?

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 $g \in G$), $H \cap K = \{\mathbb{1}\}$ and $HK = G$, then we write $G = H \rtimes K$.
For the space group $\mathcal{S} = \mathcal{P} \ltimes \Gamma$ 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

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

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 $|q\rangle_R \otimes \alpha^x_{-1}|p\rangle_L$ ($x = M = 2, \ldots, 9$ or $x = I = 10, \ldots, 25$) associated to $g = (\mathbb{1}, 0)$
- Massless spectrum:
  - Graviton $g_{\mu\nu}$, dilaton φ and anti-symmetric tensor $B_{\mu\nu}$ in 4D ($\mu = 2, 3$)

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

  - Geometric moduli

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

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

- Massless spectrum:
  - 16 chargeless gauge bosons

$$|q\rangle_R \otimes \alpha^I_{-1}|0\rangle_L,$$

  q as in (55) and $I = 10, \ldots, 25$.
  - 480 charged gauge bosones

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

  such that $q \cdot v_h = 0$ mod 1 (q as in (55)) and $p \cdot V_h = 0$ mod 1, then $p \cdot V = 0$ mod 1 and $p \cdot A_\alpha = 0$ mod 1, $\alpha = 1, \ldots, 6$.
  - Non-twisted charged matter fields. States as in (56) such that

$$p \cdot V_h - q \cdot v_h = 0 \quad \text{mod } 1,$$

  where q is **not** of the form (55).

$\alpha_{1,2}$ 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^a_R are the matrices associated to the generators in the rep $\mathbf{R}$, then

$$\mathrm{Tr}[T^a_R T^b_R] = C(\mathbf{R})\delta^{ab},$$

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 $[T^a_R, T^b_R] = if^{abc}T^c_R$, 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 $g_s^{-2} = \langle \mathrm{Re}S \rangle$ at $M_{\mathrm{str}} \approx 10^{17}$ GeV.

Compactification and effective vacua details

- Two point groups $\mathbb{Z}_8$–I and $\mathbb{Z}_8$–II with $v_{\text{I}} = \frac{1}{8}(1, 2, -3)$ and $v_{\text{II}} = \frac{1}{8}(1, 3, -4)$
- 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]
- 138 inequivalent space groups for 17 abelian point groups with $\mathcal{N} = 1$
  M. Fischer [arXiv:hep-th/1209.3906]

Orbifolio	# 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

Orbifolio	# 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: $\alpha_{\mathsf{GUT}} \equiv \alpha_1(M_{\mathsf{GUT}}) = \alpha_2(M_{\mathsf{GUT}})$ implies $(\Lambda_{\mathsf{SUSY}} = \Lambda_{Z'})$

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

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

- Diagonal lines:

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

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 $\Lambda_{\mathsf{SUSY}} = 10^{12}$ GeV $\approx M_{\mathsf{GUT}}$ 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 $A_6 = 0$.
- $t_1 = \frac{1}{4}(1, \frac{5}{3}, \frac{5}{3}, -\frac{5}{3}, 1, 1, 1, 1)(0, 0, 0, 0, 0, 0, 0, 0)$
- $t_4 = \frac{1}{12\sqrt{2}}(-3, 0, 0, 0, 1, 1, 1, -2)(0, 0, 0, 0, 0, 8, 8, 0)$
- $M_{\mathsf{GUT}} \approx 10^{12}$ GeV, $\alpha_{\mathsf{GUT}} \approx 1/32$, $\alpha_4^{-1}(2\ \text{TeV}) \approx 54$
- $b_i = (23/3, -1/3, -19/3, 715/108)$ and $b_i^{\mathsf{SUSY}} = (59/5, 5, -2, 731/72)$

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]

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

- 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

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

where

$$Y_2(S) \equiv \mathrm{Tr}\left[3h_u^\dagger h_u + 3h_d^\dagger h_d + h_e^\dagger h_e\right],$$
$$H(S) \equiv \mathrm{Tr}\left[3(h_u^\dagger h_u)^2 + 3(h_d^\dagger h_d)^2 + (h_e^\dagger h_e)^2\right],$$

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

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

Mass generation

Dominant contributions to the mass terms (effective Lagrangian)

$$\mathcal{L} \supset -h^u_{33}\overline{u}_3\widetilde{\phi}^\dagger_u q_3 - h^u_{11,22}\bar{u}_{1,2}\widetilde{\phi}^\dagger_u q_{1,2}s_2^2 - h^d_{33}\bar{d}_3\widetilde{\phi}^\dagger_d q_3 s_1^7 s_2^2 - h^d_{11,22}\bar{d}_{1,2}\widetilde{\phi}^\dagger_d q_{1,2}s_2^2$$
$$-h^e_{33}\bar{e}_3\widetilde{\phi}^\dagger_d \ell_3 s_1^2 - h^e_{11,22}\bar{e}_{1,2}\widetilde{\phi}^\dagger_d \ell_{1,2}s_2^2 - h^\nu_{ii}N^b_i\widetilde{\phi}^\dagger_u \ell_3 s_2^2 - k_{ij}N^a_i N^c_j s_1 + \text{h.c.},$$

where $\widetilde{\phi}_{u,d}$ 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
- $V_1 = \frac{1}{4}(-5,-1,1,1,1,1,1,1)(-7,-7,-1,-1,-1,-1,1,1)$
  $V_2 = \frac{1}{8}(5,-3,-7,-1,-1,1,1,5)(-7,-3,-1,1,1,7,-7,5)$
- $A_1 = A_2 = 0,$
  $A_3 = A_4 = A_6 = \frac{1}{4}(-7,5,5,3,3,-3,1,5)(1,1,7,1,3,5,9,9),$
  $A_5 = (0,0,0,0,0,0,0,0)(0,1,-2,1,1,1,2,-2)$