Phenomenology of non-supersymmetric string models

In collaboration with Steven Abel and Keith R. Dienes

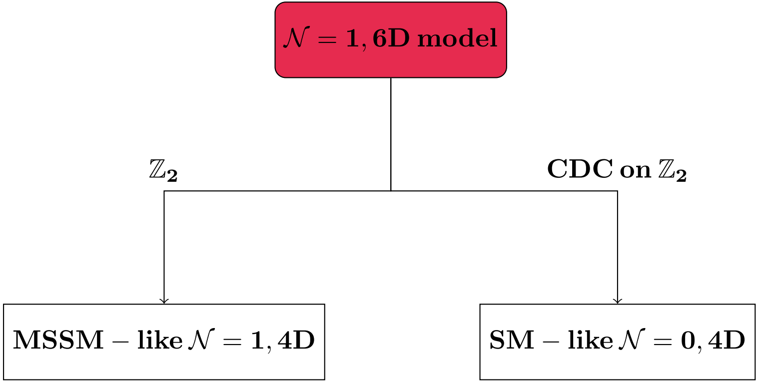
Eirini Mavroudi

11-06-2015

StringPheno ’15
IFT Madrid, Spain

- String pheno has been marked by a notable progress in the construction of 'realistic' or 'semi-realistic' string models with $\mathcal{N}=1$ SUSY.
- There has been some effort in the construction of non-SUSY models.
  [Dixon Harvey; Gato-Rivera, Schellekens; Ferrara, Kounnas, Porrati, Zwirner; Kounnas, Rostand; Angelatonj, Antoniadis, Forger; Blumenhagen, Font; Keith Dienes; Groot-Nibbelink, Loukas, Ramos-Sanchez; Faraggi, Kounnas, Partouche ...]
- Purpose of our work:
  - Construct modular invariant, tachyon-free, non-SUSY models from *heterotic* strings via a CDC.
  - *Stable* models with an almost vanishing 1-loop cosmological constant / dilation tadpole.
  - A SM-like theory emerges at the low energy limit of the non-SUSY model.

Starting Point



$\mathcal{N}=1,6D$ model

Sector	ψ^{34}	ψ^{56}	χ^{34}	y^{34}	ω^{34}	χ^{56}	y^{56}	ω^{56}	$\bar{y}^{34}$	$\bar{\omega}^{34}$	$\bar{y}^{56}$	$\bar{\omega}^{56}$	$\bar{\psi}^{1}$	$\bar{\psi}^{2}$	$\bar{\psi}^{3}$	$\bar{\psi}^{4}$	$\bar{\psi}^{5}$	$\bar{\eta}^{1}$	$\bar{\eta}^{2}$	$\bar{\eta}^{3}$	$\bar{\phi}^{1}$	$\bar{\phi}^{2}$	$\bar{\phi}^{3}$	$\bar{\phi}^{4}$	$\bar{\phi}^{5}$	$\bar{\phi}^{6}$	$\bar{\phi}^{7}$	$\bar{\phi}^{8}$
V_0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V_1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V_2	1	1	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
V_5	0	0	0	0	0	0	1	1	0	1	0	0	1	1	1	0	0	0	0	0	1	1	1	1	0	0	1	1
V_6	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0
V_7	0	0	0	1	1	0	0	0	1	0	1	0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1	$\frac{1}{2}$

Spin structure of this model with *complexified* w/s fermions. Each entry of the table $\equiv$ B.C of the w/s fermions and is multiplied by a factor of $-1/2$.

$0 \equiv$ antiperiodic B.C $\rightarrow$ NS fermions, $-1/2 \equiv$ periodic B.C $\rightarrow$ R fermions.

- This spin structure guarantees that
  - the w/s SUSY is preserved,
  - the model is modular invariant,
  - the w/s supercurrent is invariant under the B.C of the w/s fermions

$$T_F(z) = \psi^\mu(z)\partial_z X_\mu(z) + \sum_{I=3}^{I=D} \chi^I y^I \omega^I \,, \tag{1}$$

    $\mu = 3, \ldots, D.$
  - there are no conformal anomalies.

$\mathcal{N} = 1, 4D$ model

Chiral $SU(3) \otimes SU(2) \otimes U(1)_Y$

Sector	ψ^{34}	ψ^{56}	χ^{34}	y^{34}	ω^{34}	χ^{56}	y^{56}	ω^{56}	$\bar{y}^{34}$	$\bar{\omega}^{34}$	$\bar{y}^{56}$	$\bar{\omega}^{56}$	$\bar{\psi}^1$	$\bar{\psi}^2$	$\bar{\psi}^3$	$\bar{\psi}^4$	$\bar{\psi}^5$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^1$	$\bar{\phi}^2$	$\bar{\phi}^3$	$\bar{\phi}^4$	$\bar{\phi}^5$	$\bar{\phi}^6$	$\bar{\phi}^7$	$\bar{\phi}^8$
V_0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V_1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V_2	1	1	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
b_3	1	0	$\bar{1}$	0	$\bar{0}$	$\bar{0}$	0	$\bar{1}$	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0
b_4	1	0	$\bar{0}$	0	$\bar{1}$	$\bar{1}$	0	$\bar{0}$	0	1	0	0	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0
V_5	0	0	0	$\bar{0}$	$\bar{0}$	0	$\bar{1}$	$\bar{1}$	0	1	0	0	1	1	1	0	0	0	0	0	1	1	1	1	0	0	1	1
V_6	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0
V_7	0	0	0	$\bar{1}$	$\bar{1}$	0	$\bar{0}$	$\bar{0}$	1	0	1	0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1	$\frac{1}{2}$

Spin structure of this model with *real* w/s fermions and 2 bosonic coordinates compactified on a $\mathbb{Z}_2$ orbifold. The table entries are explicitly $1 = (11)_r$, $0 = (00)_r$, $\bar{1} = (10)_r$, $\bar{0} = (01)_r$. b_3 and b_4 are $\mathbb{Z}_2$ twists.

- The $\mathbb{Z}_2$ projection on the R free-fermions ϕ is

$$\widehat{\mathrm{g}}\phi = \begin{cases} \phi\widehat{\mathrm{g}} & \phi \notin b_3 \text{ or } b_4 \\ -\phi\widehat{\mathrm{g}} & \phi \in b_3 \text{ or } b_4, \end{cases} \tag{2}$$

  $\widehat{\mathrm{g}}$ is the $\mathbb{Z}_2$ generator, $\widehat{\mathrm{g}}^2 = 1$.

- The $\mathbb{Z}_2$ action is consistent with the global invariance of $T_F(z)$,

$$\widehat{\mathrm{g}}T_F(z) = -T_F(z)\widehat{\mathrm{g}}. \tag{3}$$

- $\mathcal{N} = 1, 6D \xrightarrow{CDC \text{ on } \mathbb{Z}_2} 4D$ with $\mathcal{N} = 1$ *spontaneously broken*.
- The symmetries of the $T_F(z)$ that induce the SSB are *discrete rotations* $\subset U(1) \subset SO(4)$. [Kounnas, Rostand]
- The w/s Lagrangian, $\mathfrak{L}_w$, is deformed via a local generator $\mathbf{Q}$ of the J_1 discrete symmetry which partly involves the R-symmetry. [Ferrara, Kounnas, Porrati, Zwirner]
  - The s/t gravitinos must transform non-trivially under its action and

$$[T_F(z), \mathbf{Q}(z)] \neq 0\,. \tag{4}$$

- $J_1 : f_c \to e^{2\pi i \mathbf{e}_c} f_c$. The operator, $\widehat{\alpha}_1 = e^{2\pi i \mathbf{e}\cdot\mathbf{Q}}$,
  - must be globally defined on the w/s,
  - obey the $\mathbb{Z}_2$ consistency condition: $\{\mathbf{e}\cdot\mathbf{Q}, \widehat{\mathrm{g}}\} = 0$

    $\mathbf{e}$ is the J_1 charge of the w/s fermions.
    For $\mathbf{e} = 1/2\left[0\,0\;\;1\,0\,1\;\;1\,0\,1 \mid (0)^{20}\right]$,

$$\begin{aligned} \mathbf{e}\cdot\mathbf{Q} &= \frac{1}{2}\frac{1}{2\pi i}\int dz\,(\overline{\chi}^{34}\chi^{34} + \overline{\chi}^{56}\chi^{56} + \overline{\omega}^{34}\omega^{34} + \overline{\omega}^{56}\omega^{56}) \\ &= \frac{1}{2}\left(Q_{\chi^{34}} + Q_{\chi^{56}} + Q_{\omega^{34}} + Q_{\omega^{56}}\right)\,. \end{aligned} \tag{5}$$

- SSB occurs *only* in the untwisted sectors of the theory. The CDC one-loop p.f is given by

$$\mathcal{Z}(\tau)=\sum_{m_{1,2},n_{1,2}} Tr\ \mathrm{g} q^{[\mathbf{L'}_0]}\bar{q}^{[\overline{\mathbf{L'}}_0]}=\underbrace{(D-2)q^{-1}}_{proto\ gravitons}+\dots \tag{6}$$

g is the GSO projection - independent of the CDC vector $\mathbf{e}$.

$$\begin{aligned}\mathbf{L'}_0 =& \boxed{\frac{1}{2}\left[\mathbf{Q}_L-\mathbf{e}_L(n_1+n_2)\right]^2}+\boxed{\frac{1}{4}\left[\frac{m_1+\mathbf{e}\cdot\mathbf{Q}-\frac{1}{2}(n_1+n_2)\mathbf{e}^2}{r_1}+n_1r_1\right]^2}\\ &+\frac{1}{4}\left[\frac{m_2+\mathbf{e}\cdot\mathbf{Q}-\frac{1}{2}(n_1+n_2)\mathbf{e}^2}{r_2}+n_2r_2\right]^2-1+\text{ other osc. cont's}\\ \overline{\mathbf{L'}}_0 =& \frac{1}{2}\left[\mathbf{Q}_R-\mathbf{e}_R(n_1+n_2)\right]^2+\frac{1}{4}\left[\frac{m_1+\mathbf{e}\cdot\mathbf{Q}-\frac{1}{2}(n_1+n_2)\mathbf{e}^2}{r_1}-n_1r_1\right]^2\\ &+\frac{1}{4}\left[\frac{m_2+\mathbf{e}\cdot\mathbf{Q}-\frac{1}{2}(n_1+n_2)\mathbf{e}^2}{r_2}-n_2r_2\right]^2-\frac{1}{2}+\text{ other osc. cont's}\end{aligned} \tag{7}$$

- In SSB the lightest states get a mass

$$\alpha'\mathbf{m}^2=|\mathbf{e}\cdot\mathbf{Q}|^2\left(\frac{1}{{r_1}^2}+\frac{1}{{r_2}^2}\right) \tag{8}$$

Sector	ψ^{34}	ψ^{56}	χ^{34}	y^{34}	ω^{34}	χ^{56}	y^{56}	ω^{56}	$\bar{y}^{34}$	$\bar{\omega}^{34}$	$\bar{y}^{56}$	$\bar{\omega}^{56}$	$\bar{\psi}^1$	$\bar{\psi}^2$	$\bar{\psi}^3$	$\bar{\psi}^4$	$\bar{\psi}^5$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^1$	$\bar{\phi}^2$	$\bar{\phi}^3$	$\bar{\phi}^4$	$\bar{\phi}^5$	$\bar{\phi}^6$	$\bar{\phi}^7$	$\bar{\phi}^8$
V_0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V_1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V_2	1	1	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
b_3	1	0	$\bar{1}$	0	$\bar{0}$	$\bar{0}$	0	$\bar{1}$	0	0	0	1	1	1	1	1	1	0	1	0	0	0	1	1	1	0	0	1
V_4	0	0	1	0	1	1	0	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
V_5	0	0	0	$\bar{0}$	$\bar{0}$	0	$\bar{1}$	$\bar{1}$	0	1	0	1	1	1	1	0	0	0	1	0	0	0	1	0	0	1	1	1
V_7	0	0	0	$\bar{1}$	$\bar{1}$	0	$\bar{0}$	$\bar{0}$	0	1	0	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	0	1	1	0	0	0	0
e	0	0	1	0	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1

Spin structure of the *tachyon-free*, non-SUSY model. The self-consistent GSO projections from the V_1 sector project out the ”physical” tachyons.

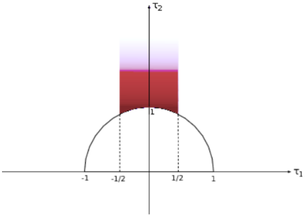
- The multiplets with the
  - Gravity & SM particle content correspond to *unbroken* generators of the symmetry: $\rightarrow e \cdot \mathbf{Q} = 0 \Rightarrow$ Massless particles.
  - Susy partners correspond to *broken* generators of the symmetry: $\rightarrow e \cdot \mathbf{Q} = -1/2 \Rightarrow$ Massive particles, $m = \frac{1}{2}\sqrt{r_1^{-2} + r_2^{-2}}$.
- Interpolating model $\xrightarrow{Low\ energy\ limit}$ SM-like theory $>$ 3 chiral generations.

1-loop Cosmological Constant / Dilaton Tadpole

$$\Lambda^{(D)} \equiv -\frac{1}{2}\mathcal{M}^D \int_{\mathcal{F}} \frac{d^2\tau}{{\tau_2}^2} \mathcal{Z}(\tau) \quad (9)$$

$\mathcal{M} = \frac{1}{\sqrt{\alpha'}}$, $D =$ uncompactified dim

$$\mathcal{F} \equiv \{\tau : |\mathrm{Re}\,\tau| \leq \frac{1}{2}, \mathrm{Im}\,\tau > 0, |\tau| \geq 1\}$$



- The Λ of a tachyon-free $\mathcal{N}=0, 4D$ model gets contributions from the
  - *Unphysical* states - proto gravitons in $(\tau_2 < 1)$:

$$\Lambda^{(0,-1)} \sim \frac{\sqrt{2}}{\pi} e^{-2\pi(\ell+n)} (r_1 r_2)^2 e^{-\pi(r_1 r_2)^2} \quad (10)$$

  - *Physical* states in $(\tau_2 \geq 1, -1/2 \leq \tau_1 \leq 1/2)$. The dominant factor comes from the sectors with odd ℓ_i and $n_i = 0$:

$$\Lambda = r_1 r_2 \mathcal{M}^4 \int_{\frac{1}{\mu^2}\approx 1}^{\infty} \frac{d\tau_2}{\tau_2^4} \sum_{\substack{\ell=odd \\ level\ i}} (N_f^i - N_b^i) e^{-\frac{\pi}{\tau_2}|\underline{\ell}|^2} e^{-\pi\tau_2\alpha' m_i^2} \quad (11)$$

$[\underline{\ell} = (r_1\ell_1, r_2\ell_2), \underline{n} = (r_1 n_1, r_2 n_2)]$ = resumed KK and winding modes. In the large r_1, r_2 limit the $n_i \neq 0$ give extremely suppressed contributions.

Exponential suppression

1. Assuming that $r_1 < r_2$, the massless physical states give

$$\begin{aligned}\Lambda_0 &= \frac{2r_1r_2\mathcal{M}^4}{\pi^3}(N_f^0 - N_b^0)\sum_{\ell=odd}|\underline{\ell}|^{-6}\left(1-\mathcal{O}(e^{-\pi|\underline{\ell}|^2\mu^2})\right)\\ &= \frac{4r_1r_2\mathcal{M}^4}{\pi^3}(N_f^0 - N_b^0)(2r_1)^{-6}\zeta(6,\frac{1}{2}) + \dots\\ &= r_1r_2\mathcal{M}^4(N_f^0 - N_b^0)\frac{\pi^3}{240{r_1}^6}\,. \end{aligned} \tag{12}$$

2. The contributions of the massive physical states, found by the saddle point approximation - saddle at $\tau_2 = \frac{|\underline{\ell}|}{\sqrt{\alpha'}m_i}$ (valid for $\sqrt{\alpha'}m_i \ll 1$), is

$$\begin{aligned}\Lambda_{i\neq 0} &= r_1r_2\mathcal{M}^4(N_f^i - N_b^i)\sum_{\ell=odd}|\underline{\ell}|^{-7/2}(\sqrt{\alpha'}m_i)^{5/2}e^{-2\pi\sqrt{\alpha'}m_i|\underline{\ell}|}\\ &\times\left(1-\mathcal{O}\left(\frac{1}{2\pi|\underline{\ell}|\sqrt{\alpha'}m_i}\right)\right)\,. \end{aligned} \tag{13}$$

- The $(N_f^0 - N_b^0) = 0$ in the $\mathcal{N}=0,4D$ model $\Rightarrow \Lambda = \mathcal{O}[e^{-|\underline{\ell}|}] \sim \phi$ Hence the model is *stable* & *finite*.

Conclusion

- We constructed modular invariant heterotic string models in $4D$ with no s/t SUSY: $SO(10)$, Flipped $SU(5)$, $SO(6)\otimes SO(4)$, $SU(3)\otimes SU(2)\otimes U(1)_Y$.
- Their mass spectra involve particles (superpartners) with masses $\sim \frac{1}{R}$, for R a general radius of compactification.
- These theories have an almost vanishing cosmological constant which overcomes the stability and finiteness issues.
- Future work:
  - Study whether the exponential suppression extends beyond the 1-loop.
  - Study the precise nature of the interpolating model at the $r_1, r_2 \to 0$ limit.
  - Get a 3 generation SM.

Thank you