News on String Vacua of Particle Physics

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based on
1509.00048[hep-th] & Fortsch.Phys.62(2014)981 with **Jill Ecker, Wieland Staessens**
1507.07568[hep-th] & JHEP1407(2014)124 with **Michael Blaszczyk, Isabel Koltermann**
Fortsch.Phys.62(2014)115 with **Wieland Staessens**

DESY Theory Workshop, 30 September 2015

Motivation: String Theory - Anything Goes??

Big(gest) challenge:

- If **string theory** is unification of all fundamental interactions
  1. ...how is **particle physics** realised?
  2. ...is it **predicitive**?
  3. ...can it explain **cosmology** *simultaneously*?

1. **Particle physics:** extensive searches so far
   - (MS)SM spectrum (✓) see also talks by Vaudrevange, Mayrhofer, Oehlmann
   - gauge & Yukawa hierarchies **??**
2. **Predictivity**
   - value of M_{string} and other $M_{\text{new physics}}$ (KK, ~~SUYS~~, ...) **??**
   - discrete points in g_{string} & moduli space **??**
3. **Cosmology**
   - inflation / early universe **??** see talks by Kappl, Witkowski, Dierigl for axions
   - dark matter & dark energy **??**

This talk: SM/GUTs + viable scales + (QCD) axions

Model Building: Regimes of Validity

CFT vs. SUGRA regime:

- **CFT** only at specific corners in moduli space
- **SUGRA** @ leading order & closed/pure gauge sectors only

$\rightsquigarrow$ combination:

- systematic scans for MSSM and/or GUT spectra per bckgrd.
  - no **exact** SM without exotics **(??)** $\rightsquigarrow$ see example on next slide
- verify moduli stabilisation @ orbifold point in field theory $\rightsquigarrow$ see later

Perturbative vs. non-perturbative regime:

- **pert. Type II:** only $U(N)$, $USp(2N)$, $SO(2N)$, ~~$SO(10)_{\text{GUT}}$~~
  - Pati-Salam, L-R sym. & SM groups *'natural'*
  - $U(1)_{\text{massless}}$ & $\mathbb{Z}_n \subset U(1)_{\text{massive}}$ well understood $\rightsquigarrow$ for coupling selection rules & $U(1)_{PQ}$ see later
- **het.** $E_8 \times E_8 \leftrightarrow$ **F-theory** $\rightsquigarrow$ see other parallel talks

Ex: MSSM on rigid D6-branes on $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_6 \times \Omega\mathcal{R})$

Ecker, **G.H.**, Staessens '15

- **MSSM matter** of $\boxed{(SU(3)_a \times USp(2)_b \times SU(4)_h)^{(U(1)_{PQ}),\mathbb{Z}_3}_{U(1)_Y}}$:

$$3 \times \left[(\mathbf{3},\mathbf{2},\mathbf{1})^{(0),0}_{1/6} + \underbrace{2 \times (\overline{\mathbf{3}},\mathbf{1},\mathbf{1})^{(1),1}_{1/3} + (\mathbf{3},\mathbf{1},\mathbf{1})^{(1),1}_{-1/3}} + (\overline{\mathbf{3}},\mathbf{1},\mathbf{1})^{(1),1}_{-2/3}\right]$$

$$+ 3 \times \left[\underbrace{(\mathbf{1},\mathbf{2},\mathbf{1})^{(1),1}_{1/2} + 2 \times (\mathbf{1},\mathbf{2},\mathbf{1})^{(1),1}_{-1/2}} + (\mathbf{1},\mathbf{1},\mathbf{1})^{(-2),1}_{0} + (\mathbf{1},\mathbf{1},\mathbf{1})^{(0),0}_{1}\right]$$

$$= 3 \times \left[Q_L + \overbrace{2 \times d_R + \overline{d_R}} + u_R\right] + 3 \times \left[\overbrace{H_u/\overline{L} + 2 \times L} + \nu_R + e_R\right]$$

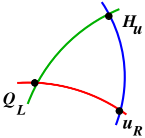
- **Higgses**: $3 \times \left[(\mathbf{1},\mathbf{2},\mathbf{1})^{(1),1}_{1/2} + h.c.\right] + \tilde{2} \times \left[(\mathbf{1},\mathbf{2},\mathbf{1})^{(-1),2}_{1/2} + h.c.\right]$
- **axions:** $3 \times [\Sigma^{cd} + \tilde{\Sigma}^{cd}] = \mathbf{3} \times \left[(\mathbf{1},\mathbf{1},\mathbf{1})^{(-2),1}_{\mathbf{0}} + \mathbf{h.c.}\right]$
- **vector-like states:** $(5_{\mathbf{Anti}_b} + 4_{\mathbf{Adj}_c} + 5_{\mathbf{Adj}_d}) \times (\mathbf{1},\mathbf{1},\mathbf{1})^{(0),0}_{0} +$

$$+ \left[2 \times (\mathbf{3},\mathbf{1},\overline{\mathbf{4}})^{(0),1}_{1/6} + (\mathbf{3},\mathbf{1},\mathbf{4})^{(0),2}_{1/6} + 2 \times (\mathbf{3_A},\mathbf{1},\mathbf{1})^{(0),0}_{1/3} + h.c.\right]$$

$$+ \left[3 \times (\mathbf{1},\mathbf{1},\mathbf{1})^{(0),0}_{1} + (\mathbf{1},\mathbf{1},\mathbf{1})^{(-2),1}_{1} + 2 \times (\mathbf{1},\mathbf{1},\mathbf{6_A})^{(0),1}_{0} + h.c.\right]$$

$$+ 3 \times (\mathbf{1},\mathbf{2},\mathbf{4})^{(0),2}_{0} + 6 \times (\mathbf{1},\mathbf{1},\overline{\mathbf{4}})^{(-1),0}_{-1/2} + 3 \times (\mathbf{1},\mathbf{1},\overline{\mathbf{4}})^{(-1),0}_{1/2} + 3 \times (\mathbf{1},\mathbf{1},\mathbf{4})^{(-1),1}_{1/2}$$

Ex: Yukawa Hierarchies via Unisotropic Compactifications



- consider $y_u^{(ijk)}\, Q_L^{(i)} \cdot \tilde{H}_u^{(j)}\, u_R^{(k)}$, e.g.:

off-diagonal	diagonal
$y_u^{(221)} \sim \mathcal{O}\left(e^{-\frac{16v_2+v_3}{48}}\right)$	$y_u^{(121)} \sim \mathcal{O}\left(e^{-\frac{4v_2+v_3}{48}}\right)$
$y_u^{(312)} \sim \mathcal{O}\left(e^{-\frac{v_2+16v_3}{48}}\right)$	$y_u^{(313)} \sim \mathcal{O}\left(e^{-\frac{v_2+4v_3}{48}}\right)$

v_i: volume of $T^2_{(i)}$

- 3^{rd} generation heavier if $v_3 < v_2$
- diagonal terms dominant if $v_2 < 5v_3$

$\rightsquigarrow$ *mild* **anisotropy** phenomenologically favoured

Here: free choice of parameters allows fits to phenomenologically accepted scales of couplings

$\rightsquigarrow$ fits for **gauge couplings** along same lines

Scales & Moduli - Type IIA/$\Omega\mathcal{R}$ Formalism

Type IIB/Ω: c.s. $\leftrightarrow$ Kähler moduli

- **Yukawas** depend on
  - (bulk) Kähler moduli
  - vevs of various Higgses
- **gauge couplings** depend on
  - **@ tree level:** 3-cycle volumes & $1/g_{\text{string}}$ $\quad \left(\sim \sqrt{M_{\text{Planck}}/M_{\text{string}}}\right)$
  - **@ 1-loop:** (bulk) Kähler moduli (linearly)

$\rightsquigarrow$ need to perform comprehensive parameter scan in the future

preliminary result: (i) $M_{\text{string}} \ll M_{\text{GUT}}$ possible; (ii) unisotropic tori phenom. appealing

- <u>twisted</u> Kähler moduli **decoupled** from gauge sector

$\rightsquigarrow$ flux moduli stabilisation *in principle* possible - but necessary?

- <u>twisted</u> complex structures couple to **D-branes** via

$$\Pi_a^{\text{frac}} = \frac{1}{4}\left(\Pi_a^{\text{bulk}} + \sum_{i=1}^{3} \Pi_a^{\mathbb{Z}_2^{(i)}}\right) \overset{SO/USp(2)_a}{\underset{\underset{\neq}{U(1)_a}}{=}} \Omega\mathcal{R}(\Pi_a^{\text{frac}})$$

Compl. Structure Moduli Stabilisation @ Orbifold Point

Blaszczyk, **G.H.**, Koltermann '14-15

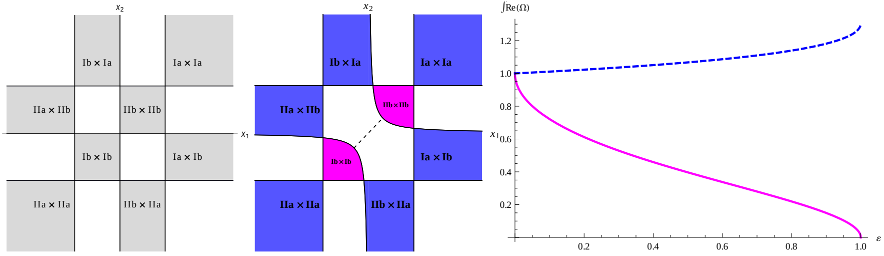
$$\Pi_a^{\text{frac}} = \frac{1}{4}\left(\Pi_a^{\text{bulk}} + \sum_{i=1}^{3} \Pi_a^{\mathbb{Z}_2^{(i)}}\right) \underset{\underset{\neq}{U(1)_a}}{\overset{SO/USp(2)_a}{=}} \Omega\mathcal{R}(\Pi_a^{\text{frac}})$$

- naively: D-brane wrapping cycle
  - **U(1)** has D-term $\rightsquigarrow$ **one** (compl. struc.) **modulus** stabilised
- but here: twisted moduli $= 0$ @ singularity:
  deformations can be studied using hypersurface formalism
  & computing $\boxed{\int_{\Pi_a}\Omega_3 \overset{\text{SUSY}}{=} \int_{\Pi_a}\Re(\Omega_3)}$
  - $SO/USp(2)$: any deformation preserves SUSY
  - $U(1)$: deformations $\rightsquigarrow$ ~~SUSY~~

$\rightsquigarrow$ **D-brane** on $\Pi_a^{\text{frac}} \neq \Omega\mathcal{R}(\Pi_a^{\text{frac}})$ **stabilises** *(all)* compl. structures which it couples to **@ orbifold point**

Ex: 10 (of 15) c.s. moduli stabilised in a PS model on $\mathbb{Z}_2 \times \mathbb{Z}_6'$

Intermezzo: Some Technicalities



- $\boxed{T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2)}$ described by hypersurface in $\otimes_{i=1}^{3} \mathbb{P}^2_{112}$:

$$y = \sqrt{(x_1^2-1)(x_2^2-1)(x_1 x_2 + \varepsilon) x_3 (x_3^2 - 1)}$$

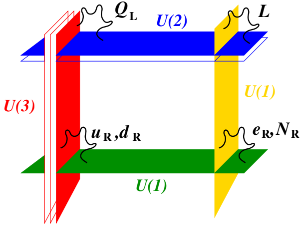
- probe **deformations** via $\boxed{\int_{\Pi_a} \Omega_3 = \int_{\Pi_a} \frac{dx_1 dx_2 dx_3}{y} \overset{\text{SUSY}}{=} \int_{\Pi_a} \Re(\Omega_3)}$ $\leftrightarrow \frac{1}{g^2_{a,\text{tree}}}$
  - $\boxed{\varepsilon > 0}$ $\Pi_a^{\mathbb{Z}_2} = \Pi_{a'}^{\mathbb{Z}_2}$, SUSY✓
  - $\boxed{\varepsilon < 0}$ $\Pi_a^{\mathbb{Z}_2} = -\Pi_{a'}^{\mathbb{Z}_2}$, ~~SUSY~~

- of interest: $\boxed{T^6/(\mathbb{Z}_2 \times \mathbb{Z}_6^{(\prime)}) \simeq [T^6(\mathbb{Z}_2 \times \mathbb{Z}_2)]/\mathbb{Z}_3^{(\prime)}}$

Towards Cosmology: Open String Axions

- **QCD axion** can be realised as **open string** state   G.H., Staessens '13

- **limited choice** of $\boxed{U(1)_{PQ}}$
  $(\perp U(1)_Y = \frac{U(1)_a/3 + U(1)_c + U(1)_d}{2})$
  - $U(1)_b$ with $(\mathbf{1}_{\mathbf{Anti}_b})_2$ or $(\mathbf{1}_{\overline{\mathbf{Anti}_b}})_{-2}$
  - **or** $U(1)_{c-d}$ with $(\mathbf{1}^{cd})_{\pm 2}$
    $\leftrightarrow$ scalars $\tilde{\nu}_R$



- fits into **SUSY DFSZ axion model** with *twice* axion charge
  $\boxed{V = V_F + V_D + V_{\text{soft}}}$

- in the **explicit example** on $\mathbb{Z}_2 \times \mathbb{Z}_6$:   Ecker, G.H., Staessens '15
  - $U(1)_{PQ} \times \mathbb{Z}_3$ charges $\rightsquigarrow \mathcal{W}_{DFSZ} = \mu \Sigma H_u \cdot \tilde{H}_d + \tilde{\mu} \tilde{\Sigma} \tilde{H}_u \cdot H_d$
  - Σ also generates other mass terms: $\mathcal{W} \supset \kappa \overline{d}_R \Sigma d_R$

$\rightsquigarrow$ rich structure in Higgs-axion potential,
but **tuning** required for massive exotics & light SM particles

Open & Closed Axion Mixing in Field Theory

see also other talks on field theoretical axion models & Higgs inflation

- open string axion a from $\sigma = \frac{v+s(x)}{\sqrt{2}} e^{i\frac{a(x)}{v}}$
- **open** axion a mixes with **closed** axion ξ ($\leftarrow U(1)_{\text{massive}}$)

$$\zeta_{\text{massive}} = \frac{M_{\text{string}}\,\xi + qv\,a}{\sqrt{M_{\text{string}}^2 + q^2v^2}}, \qquad \alpha_{\text{massless}} = \frac{M_{\text{string}}\,a - qv\,\xi}{\sqrt{M_{\text{string}}^2 + q^2v^2}}$$

- axion **decay constants** from dim. reduction:

$$f_\zeta = \frac{\sqrt{M_{\text{string}}^2 + (qv)^2}}{2}, \qquad f_\alpha = \frac{M_{\text{string}}\,qv\sqrt{M_{\text{string}}^2 + (qv)^2}}{(M_{\text{string}}^2 - (qv)^2)}$$

- For $\boxed{M_{\text{string}} \gg v}$ (field theory regime): $\zeta \simeq \xi_{\text{closed}}$, $\alpha \simeq a_{\text{open}}$

$\rightsquigarrow$ approximation of purely **open string as QCD axion** good

Conclusions & Outlook

- different **model building** approaches **complementary**:
  - CFT $\leftrightarrow$ SUGRA
  - D-branes $\leftrightarrow$ het. $E_8 \times E_8$ / F-theory
- massless **spectra** (✓)
- **couplings** require
  - improvement of field theory
  - scans of parameter (moduli, g_{string}, M_{string}) ranges

- D-branes **stabilise** c.s. moduli @ orbifold point
- **twisted** Kähler moduli **decoupled** - stabilisation needed at all?

- candidate for **QCD axion** in **open string** sector
- **closed string** axion as inflaton?