From stringy vacua with particle physics spectrum to the effective action
- exemplified by a non-factorisable orientifold -

Gabriele Honecker

Cluster of Excellence PRISMA & Institut für Physik, JG|U Mainz

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with **Mikel Berasaluce-González & Alexander Seifert**

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Mainz Institute for Theoretical Physics

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter PRISMA

Motivation: String Phenomenology & Cosmology

Status quo: *string theory* $\equiv$ *unification of all interactions*

- **string pheno:** *(very roughly)*
  - **many** compact CY and T^6/Γ models with **SM-like spectrum** **topology** $\leftrightarrow$ **chiral matter** $\rightsquigarrow$ *machine learning techniques*

    see Vaudrevange's talk
  - **rudimentary** results on effective field theory from **dim. reduction** of **SUGRA** & **DBI** $\rightsquigarrow$ S_{EH} & $1/g^2_{U(1)/SU(N)}$
    - depends on size & shape moduli of compact space, M_{string}
    - already **Yukawas challenging** - only computable with **CFT techniques** on T^6/Γ see Liyanage's talk
- **string cosmo:** *(very roughly)*
  - **assume** that **particle physics** sector is **localized** & OK ?
  - **choose** *'global'* CY geometry to explain **inflation** ?
  - *'dial'* terms in the action for moduli stabilisation ?

  see Valenzuela's, Grimm's, Westphal's talks

moduli dep. of action relevant to particle physics & cosmology

Outline

- Motivation ✓
- Stringy vacua of particle physics
  - SM & new physics matter
  - effective action
  - example: non-factorisable orbifold
- Interplay with cosmology
  - constraints on moduli from $1/g^2$,1-loop
- Conclusions

Stringy vacua of particle physics

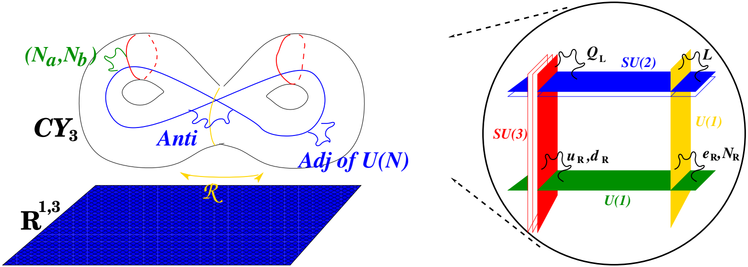
Stringy Vacua of Particle Physics: Matter Sector

Type II string theories: - and dual het. $SO(32)$ -

- **closed** strings $\rightsquigarrow$ gravity, moduli

  & some $U(1)$'s related to internal symmetries

- **open** strings $\rightsquigarrow$ $\prod U(N)$ groups & matter in **Bifund** & **Adj**
  orientifolding: $U(N) \rightarrow SO(2N)$ or $USp(2N)$ & (**Anti**)**Sym**



- **restricts** ways to realise the **SM** & **new physics**
  - two endpoints $\rightsquigarrow$ constraints on reps.
  - at least 3 kinds of D-branes
  - all couplings determined by D-brane configuration

Stringy Vacua of Particle Physics cont'd

Stringy consistency conditions:

- fix D-brane configuration - dependent on CY or T^6/Γ background
  - complete (massless) matter spectrum determined
- ensure absence of all gauge & gravitational anomalies
  - some $U(1)$'s acquire mass
  - some $\mathbb{Z}_n$'s $\subset U(1)$'s can survive $\rightsquigarrow$ selection rules on couplings
- SUSY ensures stability of vacuum @ M_{string}
  - requires ~~SUSY~~ below M_{string}

above relies on:

- **topology** of compact space

but more info on geometry required for:

- Yukawas $\propto e^{-\text{Area}_{xyz}}$
- $1/g^2_{x,\text{tree}} \propto \text{Vol}(\Pi_x)$ - D_x-brane extends along Π_x in compact space
- ... higher loop-orders and n-point couplings $\rightsquigarrow$ *all* kinds of moduli involved!

Stringy Vacua of Particle Physics: Effective Action

formal dimensional reduction of SUGRA & DBI:

- for D6-branes: $\frac{1}{g^2_{\text{tree}}} \propto \frac{\text{Vol}(\Pi_3)}{\sqrt{\text{Vol}(CY_3)}} \frac{M_{\text{Planck}}}{M_{\text{string}}}$ (compl. str. moduli)

beyond this reduction:

- only possible by CFT techniques $\leftrightarrow$ T^6/Γ or *'non-geometric'*
- Yukawas from disks w/ 3 vertex op. @ boundary (Kähler moduli)
- $\frac{1}{g^2_{\text{1-loop}}}$ also from magnetically gauged vacuum partition fct.
  - for D6-branes at angles ϕ: $\sim \ln\left(\frac{\Gamma(\phi)}{\Gamma(1-\phi)}\right)$ (compl. str. moduli)
  - for parallel D6-branes: KK & winding sums (Kähler moduli)

$$\Lambda_{0,0}(v) \equiv -\frac{1}{4\pi}\ln(\eta(iv)) \xrightarrow{v>1} \frac{v}{48}$$

$$\Lambda_{\tau,\sigma}(v) \equiv -\frac{1}{4\pi}\ln\left(e^{-\frac{\pi\sigma^2 v}{4}}\frac{|\vartheta_1(\frac{\tau-i\sigma v}{2},iv)|}{\eta(iv)}\right) \xrightarrow{v>1} \frac{\left[3(1-\sigma)^2-1\right]v}{48} - \delta_{\sigma,0}\frac{\ln[2\sin(\frac{\pi\tau}{2})]}{4\pi}$$

linear in Kähler modulus v

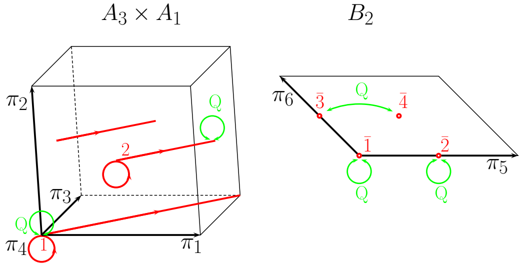
  - formulas *a priori* for factorisations $T^6 = (T^2)^3$

Example: Non-Factorizable Orientifold $T^6/\mathbb{Z}_4$

Why $\mathbb{Z}_4$ on $A_3 \times A_1 \times B_2$?

- access to compact backgrounds beyond $(T^2)^3/\Gamma$
- less twisted moduli require stabilisation: $(h_{11}^{\mathbb{Z}_2}, h_{21}^{\mathbb{Z}_2}) = (6, 2)$

  vs. $(10, 6)$ for $B_2 \times (A_1)^2 \times B_2$
- $\mathbb{Z}_4$ action given by Coxeter element on Lie algebra lattices



- construction of 3-cycles, SUSY & stringy consistency✓
  - only 2 or 4 generation models
  - but good playground

    ⇝ *non-factorisable $\mathbb{Z}_6'$ on $D_4 \times A_2$ has 3 generation models*

    (preliminary) Seifert '18

Example: Non-Factorizable Orientifold cont'd

Example: 4-generation model

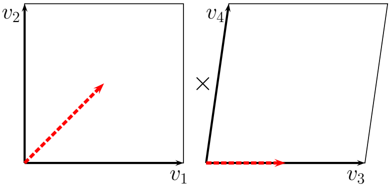
- $SU(4)_a \times USp(2)_b \times USp(2)_c \times USp(4)_h$
- $[C] = 4 \times \Big[(\mathbf{4}, \bar{\mathbf{2}}, \mathbf{1}, \mathbf{1}) + (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2}, \mathbf{1})\Big]$

↖ from topological intersection #

↙ from CFT

$$[V] = (\mathbf{15}, \mathbf{1}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{3_S}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}, \mathbf{3_S}, \mathbf{1}) + 2 \times (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{10_S}) + (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{6_A})$$
$$+ \Big(5 \times (\mathbf{6_A}, \mathbf{1}, \mathbf{1}, \mathbf{1}) + (\mathbf{10_S}, \mathbf{1}, \mathbf{1}, \mathbf{1}) + c.c.\Big) + 3 \times (\mathbf{1}, \mathbf{2}, \mathbf{2}, \mathbf{1}) + (\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{4}) + (\mathbf{1}, \mathbf{1}, \mathbf{2}, \mathbf{4})$$

- CFT methods known for factorisation $(T^2)^3$
- $(A_3 \times A_1) \times B_2 \simeq (T^2 \times T^2) \times T^2$ by shift symmetry



Example: Non-Factorizable Orientifold cont'd

- **@ tree-level:** $\frac{16\pi^2}{g^2_{x,\text{tree}}} = \frac{M_{\text{Planck}}}{M_{\text{string}}} \times \begin{cases} 2\sqrt{u_2} & \text{for } x = a \\ \frac{1}{2\sqrt{u_2}} & \text{for } x = b, c, h \end{cases}$

- **1-loop threshold corrections:**

$$\begin{aligned}
\Delta_{SU(4)_a} =& 4(\tilde{\Delta}^{\text{total}}_{aa} + \tilde{\Delta}^{\text{total}}_{aa'}) + 2\tilde{\Delta}^{\text{total}}_{ab} + 2\tilde{\Delta}^{\text{total}}_{ac} + 4\tilde{\Delta}^{\text{total}}_{ah} + \Delta^{\text{total}}_{a,\Omega\mathcal{R}} \\
=& -4\Lambda(0,0,v_1,2) - 4\Lambda(1,0,v_1,2) + 4\widehat{\Lambda}(1,0,v_1,4) \\
& -16\Lambda(0,0,v_2,u_2) - 16\Lambda(1,0,v_2,u_2) + 8\widehat{\Lambda}(0,0,v_2,2u_2) + 8\widehat{\Lambda}(1,0,v_2,2u_2) \\
& -4\Lambda(0,0,v_3,2) - 4\Lambda(1,1,v_3,2) + 4\widehat{\Lambda}(1,1,v_3,4)
\end{aligned}$$

$$\Delta_{USp(2)_{b/c}} = -4\Lambda(0,0,v_1,2) - 3\Lambda(0,0,v_2,1/u_2) + 2\widehat{\Lambda}(0,0,2v_2,2/u_2) - 4\Lambda(0,0,v_3,2) + \frac{\ln 2}{2}$$

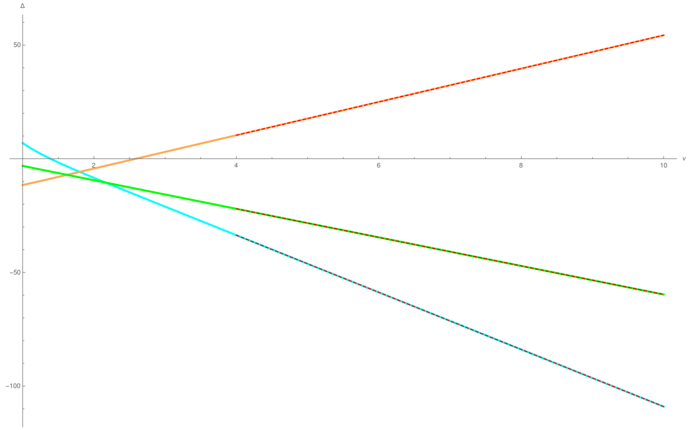
$$\Delta_{USp(4)_h} = -4\Lambda(1,0,v_1,2) - 2\Lambda(0,0,v_2,1/u_2) + 2\widehat{\Lambda}(0,0,2v_2,2/u_2) - 4\Lambda(1,1,v_3,2) + \frac{\ln 2}{2}$$

$\widehat{\Lambda}(\sigma,\tau,\ldots)$ from Möbius strip - exact shape **unknown**

Example: Pati-Salam w/ 4 Gen. cont'd: Gauge Thresholds

- (unrealistic) assumption $\widehat{\Lambda}(\sigma, \tau, \ldots) = \Lambda(0, 0, \ldots)$ for $SU(4)_a$
- universal Kähler modulus $v \equiv v_{i=1,2,3}$

$USp(2)_{b/c}$, $USp(4)_h$



$\rightsquigarrow$ enhancement/reduction of $\frac{1}{g_x^2}$ possible: fct.(Kähler modulus v)

Interplay with cosmology

Interplay with cosmology

Just to mention...

- QCD axion from open strings $\rightsquigarrow$ EFT determined
  trans-Planckian regime **not** in SUGRA approximation

Here more on hierarchies of scales:

- **tree-level:** $\frac{16\pi^2}{g^2_{x,\text{tree}}} = \frac{M_{\text{Planck}}}{M_{\text{string}}} \times \begin{cases} 2\sqrt{u_2} & \text{for } x = a \\ \frac{1}{2\sqrt{u_2}} & \text{for } x = b, c, h \end{cases}$

  with $\boxed{u_2 \propto \frac{R_1}{R_3}}$ - e.g. hierarchy $M_{\text{Planck}} \gg M_{\text{string}}, R_1 \ll R_3$ (✓)

- **1-loop threshold correction:** $\boxed{v_2 \propto R_1 R_3 > 1}$

$$\Delta_{SU(4)_a} \to \frac{2\pi}{3}\Big((1 - 2c^{(1)}_{1,0})\, v_1 - 4c^{(2)}_{1,0}\, v_2 + (1 - 2c^{(3)}_{1,1})\, v_3\Big) + \text{const.}$$

$$\Delta_{USp(2)_{b/c}} \to \frac{4\pi}{3}(v_1 - \frac{v_2}{4} + v_3) + \text{const.}$$

$$\Delta_{USp(4)_h} \to -\frac{2\pi}{3}(v_1 + v_2 + v_3) + \text{const.}$$

$\rightsquigarrow$ upper bound on LARGE volume scenario: ${}^1/g^2_{b,c,h,\text{1-loop}} \overset{v_2 \gg 1}{\lessdot} 0$ ↯ ↯

Conclusions & Outlook

Conclusions:

- stringy **particle physics**: chiral states ✓
  vector-like states (also massive) only with CFT techniques
  $\rightsquigarrow$ loop corrections computable
- **moduli** can be
  - absent by construction (here: twisted ones)
  - stabilised by D-branes $\rightsquigarrow$ FI terms
- **no separation** of **particle** $\leftrightarrow$ **cosmology** properties of string vacua due to loop effects

Outlook:

- rigorous derivation of stringy EFT needed
- popular simple cosmological scenarios need to be reconsidered