Quantum corrections to effective couplings in string theories with spontaneous supersymmetry breaking

Ioannis Florakis

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Based on work with

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M. Tsulaia

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+ work in progress

07/07/2015

8th Regional meeting in String Theory

Introduction

- 20 years of significant progress in string theory
- Semi-realistic vacua possessing basic desirable features
- Reconstruction of low energy effective action with $\mathcal{N}=1$ SUSY at tree level
- Quantitative comparison with low energy data : incorporate loop corrections

But what about SUSY breaking ?

Introduction

(stringy) Scherk-Schwarz mechanism

- Spontaneous breaking of SUSY with exactly tractable worldsheet description
- Worldsheet description in terms of freely-acting orbifolds

Scherk, Schwarz 1979
Rohm 1984
Kounnas, Porrati 1988
Atick, Witten 1988
Kounnas, Rostand 1990

When SUSY is (spontaneously) broken but the vacuum is classically stable

it is meaningful and important to study one-loop radiative corrections to couplings in the low energy effective action

Structure of the talk

Thresholds to non-abelian gauge couplings in 4d heterotic vacua $\mathcal{N}=2 \longrightarrow \mathcal{N}=0$

Universality

More realistic constructions $\mathcal{N}=1 \longrightarrow \mathcal{N}=0$ breaking and **chirality**

Vacuum configuration

Heterotic vacuum

Start with $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic string in 10d

↓ reduce on $\mathrm{K3} \sim T^4/\mathbb{Z}_N$, with N = 2, 3, 4, 6

$\mathrm{E}_8 \times \mathrm{E}_7$

$\mathcal{N} = 1$ heterotic vacuum in 6d

↓ Scherk-Schwarz reduction on T^2 + trivial Wilson line background } freely-acting $\mathbb{Z}_2'$ orbifold

$\mathrm{SO}(16) \times \mathrm{SO}(12)$ heterotic vacuum in 4d with $\mathcal{N} = 0$ SUSY

Heterotic vacuum

Consider orbifold $T^6/\mathbb{Z}_N \times \mathbb{Z}_2'$

$\mathbb{Z}_N$

$$Z^1 \to e^{2\pi i/N}\, Z^1$$
$$Z^2 \to e^{-2\pi i/N}\, Z^2$$

rotates complexified T^4 coordinates

realises singular limit of K3 surface (preserves 8 supercharges)

Alvarez-Gaumé, Ginsparg, Moore, Vafa 1986
Dixon, Harvey 1986
Itoyama, Taylor 1987

freely acting $\mathbb{Z}_2'$

$$v' = (-1)^{F_{\rm st}+F_1+F_2}\,\delta$$

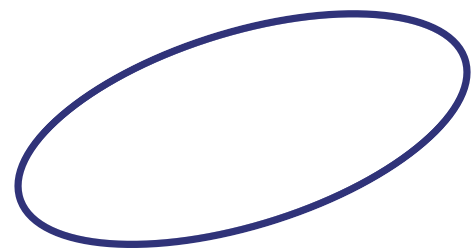
- $F_{\rm st}$: spacetime fermion number
- F_1+F_2: "fermion numbers" of original E_8's
- δ: order-2 shift along remaining T^2

responsible for spontaneous SUSY breaking down to $\mathcal{N}=0$

vacuum is classically stable (W=0)

Scherk Schwarz mechanism

Deformation of vertex operators / fields by symmetry Q

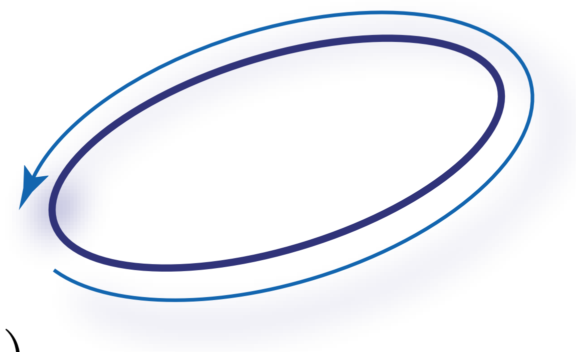


$\Phi(X_5)$

Scherk Schwarz mechanism

Deformation of vertex operators / fields by symmetry Q

$$\Phi(X_5 + 2\pi R) = e^{iQ}\,\Phi(X_5)$$



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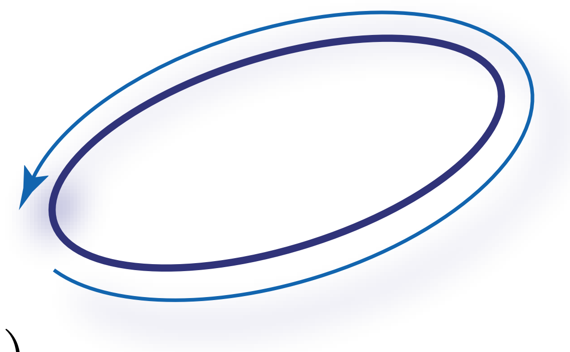


$$\Phi(X_5)$$

$$\Phi(X_5) = e^{iQX_5/2\pi R} \sum_{m\in\mathbb{Z}} \Phi_m\, e^{imX_5/R}$$

Kaluza-Klein spectrum of charged states is shifted $\quad m \to m + Q/2\pi$

$$M_{\mathrm{KK}} = \frac{|Q|}{2\pi R}$$

Scherk Schwarz mechanism

'Flat' gauging of $\mathcal{N}=2$ supergravity : completely fixed by string vacuum

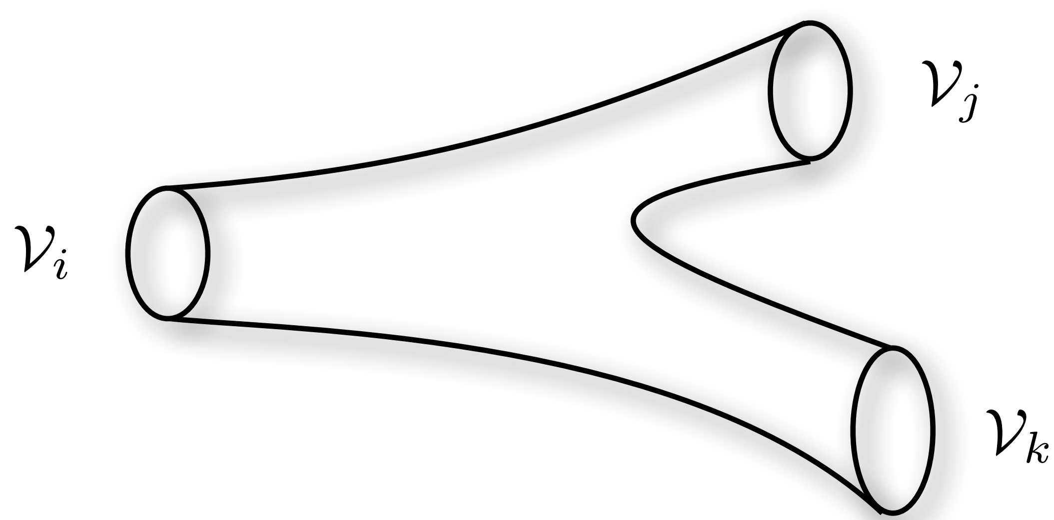
$$\frac{\mathrm{SU}(1,1)}{\mathrm{U}(1)} \times \frac{\mathrm{SO}(2,2)}{\mathrm{SO}(2)\times\mathrm{SO}(2)} \times \frac{\mathrm{SO}(4,4+n)}{\mathrm{SO}(4)\times\mathrm{SO}(4+n)}$$

S $\qquad$ T, U $\qquad$ $T_i,\ U_i,\ \Phi^A$

(BPS states $n=\infty$)

$$f_{ijk} = \langle\, \mathcal{V}_i\, \mathcal{V}_j\, \mathcal{V}_k\, \rangle_{\rm string}$$

action up to 2 derivatives fixed by the couplings among vectors and hypers



Scherk Schwarz mechanism

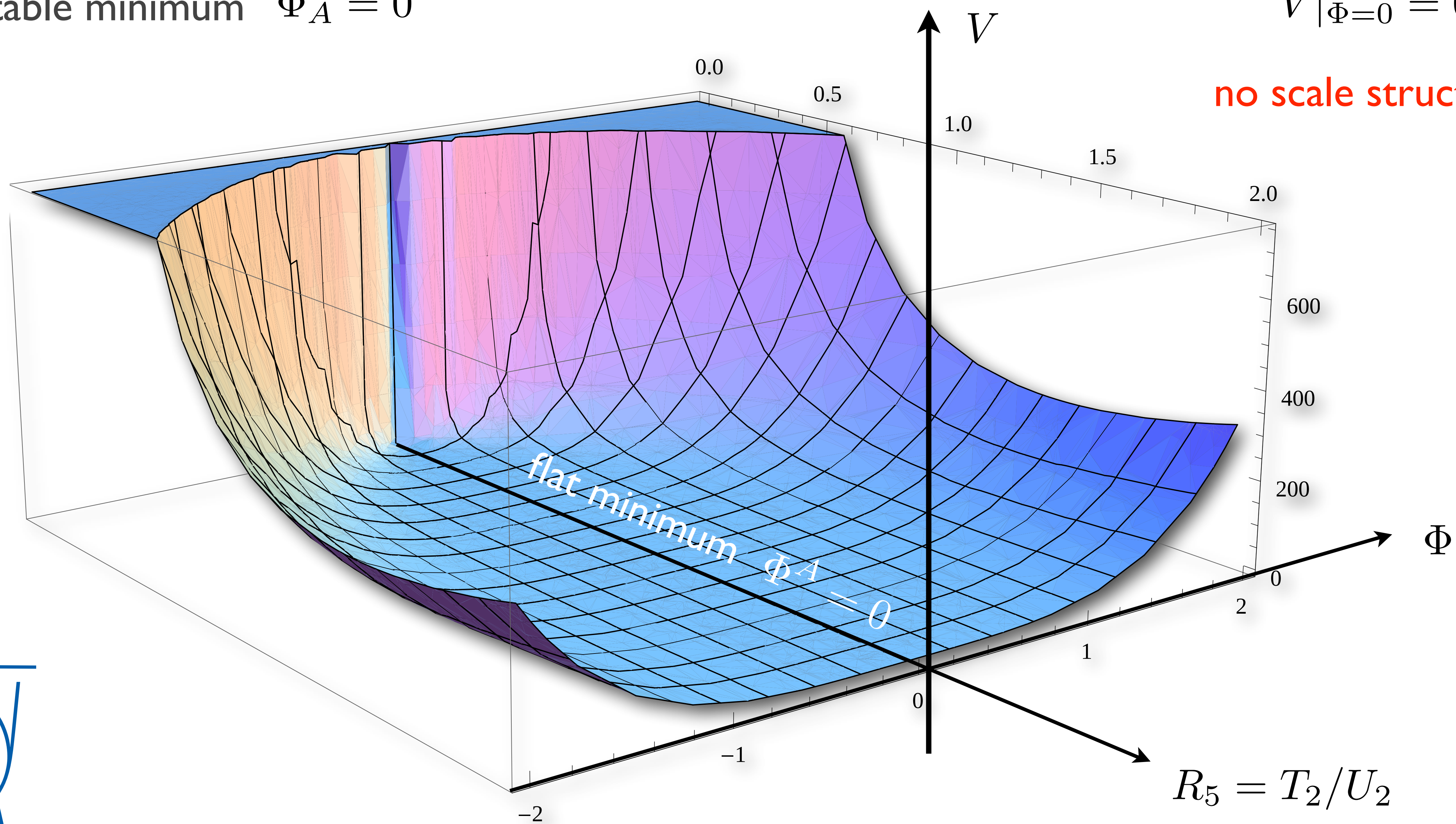
Keeping lightest BPS states $\Phi^A \in \mathbb{R}$

scalar potential $$V = \frac{|T-2U|^2\,\Phi^A\Phi_A + 2\left(|T-2U|^2 + |T-2\bar{U}|^2\right)\,(\Phi^A\Phi_A)^2}{S_2T_2U_2}$$

stable minimum $\Phi_A = 0$

$V|_{\Phi=0} = 0$

no scale structure



Scherk Schwarz mechanism

Identify extra massless states in string spectrum

$$O_4 \, O_4 \, \bar{V}_{12} \, \bar{O}_4 \, \bar{V}_{16} \;\; \times \tfrac{1}{2} \left(\mathit{\Gamma}_{2,2}[{}^{1}_{0}] + \mathit{\Gamma}_{2,2}[{}^{1}_{1}] \right)$$

bi-fundamental $(\mathbf{12}, \mathbf{16})$ of $\mathrm{SO}(12) \times \mathrm{SO}(16)$

$$m^2_{\rm BPS} = \frac{|T/2 - U|^2}{T_2 U_2} = |P_R|^2$$

no longer annihilating spacetime supercharges !

stringy Scherk-Schwarz continuously deforms masses of all states

Gauge thresholds

One loop corrections

Running coupling associated to gauge group $\mathcal{G}$

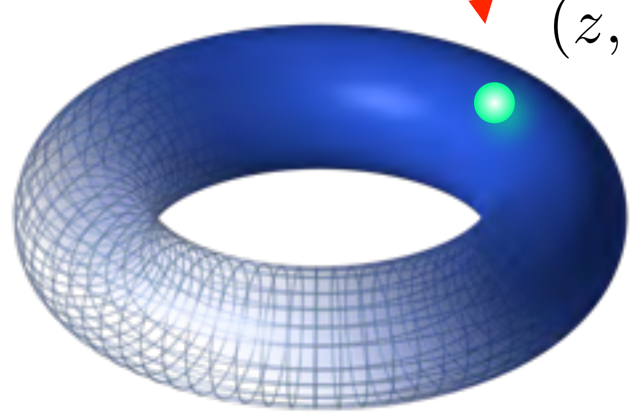
$$\frac{16\pi^2}{g^2_{\mathcal{G}}(\mu)} = \frac{16\pi^2}{g_s^2} + \beta_{\mathcal{G}} \log \frac{M_s^2}{\mu^2} + \Delta_{\mathcal{G}}$$

threshold correction

$$\frac{16\pi^2}{g^2_{\mathcal{G}}} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2} \int_{\text{torus}} d^2 z \, \langle \mathcal{V}^a(z,\bar{z}) \mathcal{V}^b(0) \rangle_{\text{CFT}}$$

one loop correction to gauge couplings

$(z, \bar{z}) \in \Sigma_1$



Supersymmetric Universality

If supersymmetry is unbroken

$$-\frac{1}{4g_{\mathcal{G}}^2} F_{\mu\nu} F^{\mu\nu}$$

BPS saturated term

only BPS states run in the loop

$$\sum_{\text{BPS states}} \text{Str}\left(\frac{1}{12} - s^2\right)\left(Q^2 - \frac{1}{4\pi\tau_2}\right) q^{\frac{1}{4}|P_L|^2 + N_{\text{osc}} - \frac{1}{2}} \bar{q}^{\frac{1}{4}|P_R|^2 + \bar{N}_{\text{osc}} - 1}$$

$$q = e^{2\pi i\tau}$$

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left moving oscillators cancel out

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Supersymmetric Universality

If supersymmetry is unbroken

Difference of thresholds for gauge group factors $\mathcal{G}_1$, $\mathcal{G}_2$

$$\Delta_{\mathcal{G}_1} - \Delta_{\mathcal{G}_2} = \int_{\mathcal{F}} d\mu \, \Gamma_{2,2}(T,U)\, \Phi(\bar{\tau})$$

holomorphic modular function (invariant)
regular everywhere

$$\Phi(\bar{\tau}) = \frac{c_{-1}}{\bar{q}} + c_0 + c_1 \bar{q} + \dots$$
$$= c_{-1} j(\bar{\tau}) + c_0$$

the pole corresponds to the bosonic vacuum of the heterotic string

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Supersymmetric Universality

If supersymmetry is unbroken

Difference of thresholds for gauge group factors $\mathcal{G}_1$, $\mathcal{G}_2$

$$\Delta_{\mathcal{G}_1} - \Delta_{\mathcal{G}_2} = \delta\beta_{12} \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2} \, \Gamma_{2,2}(T,U)$$

$$= -\delta\beta_{12} \, \log \left(T_2 U_2 \, |\eta(T)\, \eta(U)|^4 \right) + \text{constant}$$

Dixon, Kaplunovsky, Louis '91

Independently of the details of the vacuum (almost)

universality

Non-supersymmetric
Universality

Non-supersymmetric Universality

Supersymmetry is spontaneously broken

$$-\frac{1}{4g_{\mathcal{G}}^2}\,F_{\mu\nu}\,F^{\mu\nu}$$

no longer BPS saturated

ALL states run in the loop

$$\Delta_{\mathcal{G}} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2}\,\Gamma_{2,2}(T,U)\,\Phi_{\mathcal{G}}(\bar\tau)$$

previous simple expression is no longer valid

$$\Delta_{\mathcal{G}} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2}\,\frac{1}{2}\sum_{H,G=0}^{1}\Gamma_{2,2}[^H_G]\,\Phi_{\mathcal{G}}[^H_G](\tau,\bar\tau)$$

explicitly non-holomorphic

Non-supersymmetric Universality

Threshold for $\mathrm{SO}(16)$ gauge group with $\mathrm{K3}$ realized as $T^4/\mathbb{Z}_2$ orbifold

$$\Delta_{\mathrm{SO}(16)} = \int_{\mathcal{F}} d\mu \, \Bigg\{ -\frac{1}{48}\, \varGamma_{2,2}\left[{}^0_0\right] \frac{\hat{\bar{E}}_2\, \bar{E}_4\, \bar{E}_6 - \bar{E}_6^2}{\bar{\eta}^{24}}$$

BPS subsector

$$+\Gamma_{2,2}\left[{}^0_1\right] \left[-\frac{1}{4N \times 144} \frac{\varLambda^{\mathrm{K3}}\left[{}^0_0\right]}{\eta^{12}\, \bar{\eta}^{24}} (\vartheta_3^8 - \vartheta_4^8)\, \bar{\vartheta}_3^4\, \bar{\vartheta}_4^4 \left((\hat{\bar{E}}_2 - \bar{\vartheta}_3^4)\, \bar{\vartheta}_3^4\, \bar{\vartheta}_4^4 + 8\bar{\eta}^{12} \right) \right]$$

dependence on hypers

$$+\Gamma_{2,2}\left[{}^0_1\right] \left[-\frac{1}{96} \frac{\bar{\vartheta}_3^4\, \bar{\vartheta}_4^4 (\bar{\vartheta}_3^4 + \bar{\vartheta}_4^4) \left[(\hat{\bar{E}}_2 - \bar{\vartheta}_3^4)\, \bar{\vartheta}_3^4\, \bar{\vartheta}_4^4 + 8\bar{\eta}^{12} \right]}{\bar{\eta}^{24}} \right.$$

BPS subsector (exceptionally for $\mathbb{Z}_2$)

$$\left. -\frac{1}{144} \frac{\vartheta_2^4\, (\vartheta_3^8 - \vartheta_4^8)}{\eta^{12}} \frac{(\hat{\bar{E}}_2 - \bar{\vartheta}_3^4)\, \bar{\vartheta}_3^4\, \bar{\vartheta}_4^4 + 8\bar{\eta}^{12}}{\bar{\eta}^{12}} \right] + (S \cdot \tau) + (ST \cdot \tau) \Bigg\}$$

non-holomorphic

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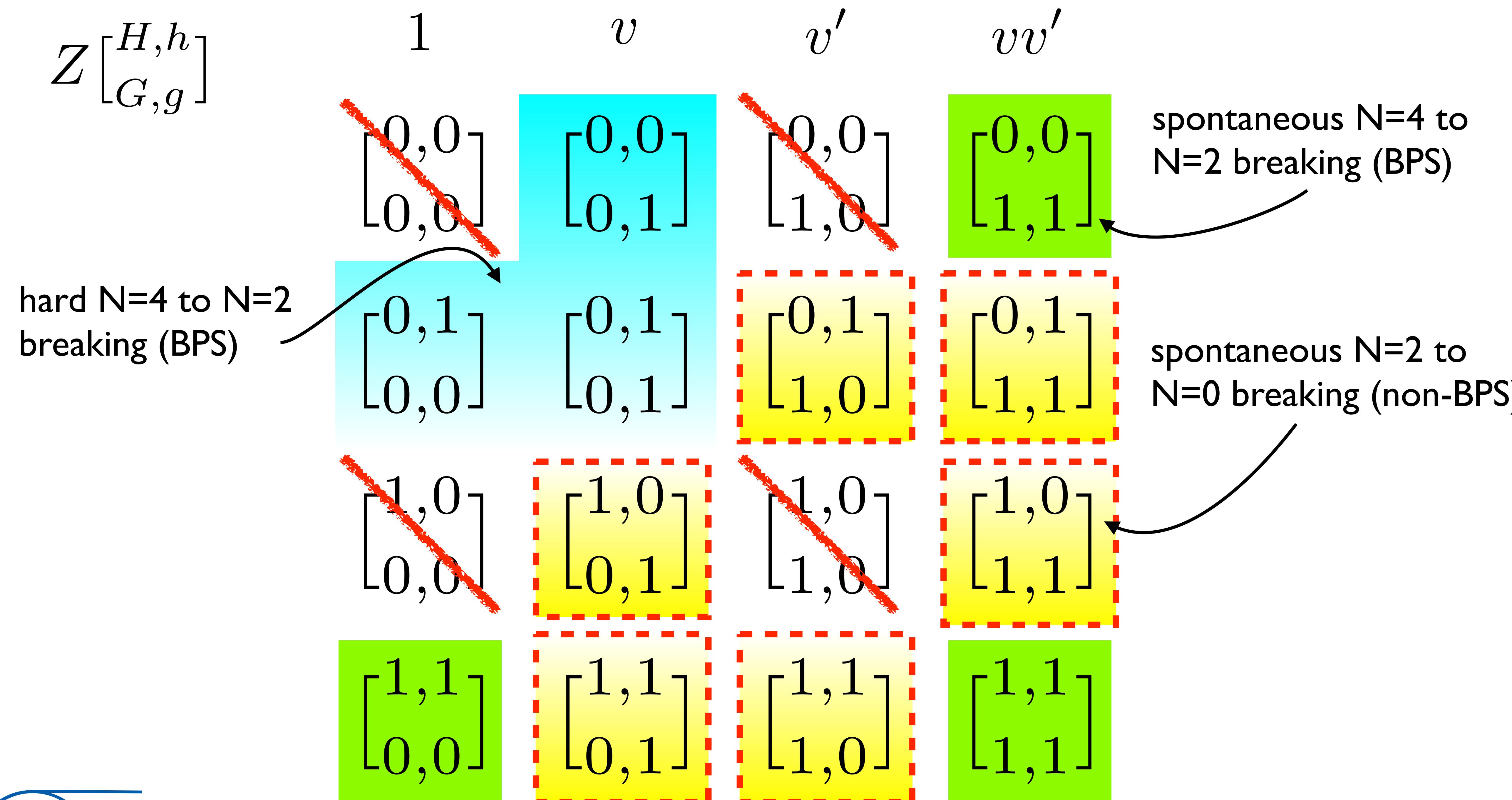
Non-supersymmetric Universality

These expressions do not look very friendly...

BUT may still be computed explicitly!

Non-supersymmetric Universality

"The anatomy of an orbifold"



Non-supersymmetric Universality

The "hard" N=4 to N=2 BPS subsector

$$\begin{bmatrix}0,0\\0,1\end{bmatrix} \quad \begin{bmatrix}0,1\\0,0\end{bmatrix} \quad \begin{bmatrix}0,1\\0,1\end{bmatrix}$$

$$= \frac{1}{2} \times (b_{\mathrm{E}_8} - b_{\mathrm{E}_7}) \times \int_{\mathcal{F}} d\mu \; \Gamma_{2,2}(T,U) = 72 \, \log T_2 U_2 |\eta(T)\eta(U)|^4$$

the theory is effectively K3xT^2

$$b_{\mathrm{E}_8} = -60$$

$$b_{\mathrm{E}_7} = -84$$

$$b_{\mathcal{G}} = \mathrm{STr}\left(\frac{1}{12} - s^2\right) Q_{\mathcal{G}}^2$$

Non-supersymmetric Universality

The spontaneous N=4 to N=2 BPS subsector

$$\begin{bmatrix}0,0\\1,1\end{bmatrix}\quad \begin{bmatrix}1,1\\0,0\end{bmatrix}\quad \begin{bmatrix}1,1\\1,1\end{bmatrix}$$

$$= \frac{1}{2} \times \left(b_{\mathrm{SO}(16)} - b_{\mathrm{SO}(12)}\right) \int_{\mathcal{F}_0(2)} d\mu \; \Gamma_{2,2}\left[{0 \atop 1}\right](T,U)$$

$$= -8\,\log T_2 U_2 |\vartheta_4(T)\vartheta_2(U)|^4$$

the theory is effectively the Z_2 orbifold $\hat{g} = g\,(-1)^{F_1+F_2}$

$$g \;:\; \begin{cases} Z^1 \to -Z^1 \\ Z^2 \to -Z^2 \\ Z^3 \to Z^3 + \frac{1}{2} \end{cases}$$

$$b_{\mathrm{SO}(16)} = 4$$

$$b_{\mathrm{SO}(12)} = -12$$

Non-supersymmetric Universality

Spontaneous N=2 to N=0 non-BPS subsector

$$\begin{bmatrix}0,1\\1,0\end{bmatrix} \quad \begin{bmatrix}0,1\\1,1\end{bmatrix}$$
$$\begin{bmatrix}1,0\\0,1\end{bmatrix} \quad \begin{bmatrix}1,0\\1,1\end{bmatrix}$$
$$\begin{bmatrix}1,1\\0,1\end{bmatrix} \quad \begin{bmatrix}1,1\\1,0\end{bmatrix}$$

$$= (1+S+TS)\cdot\left(\begin{bmatrix}0,1\\1,0\end{bmatrix} + \begin{bmatrix}0,1\\1,1\end{bmatrix} \right)$$

use to partially unfold

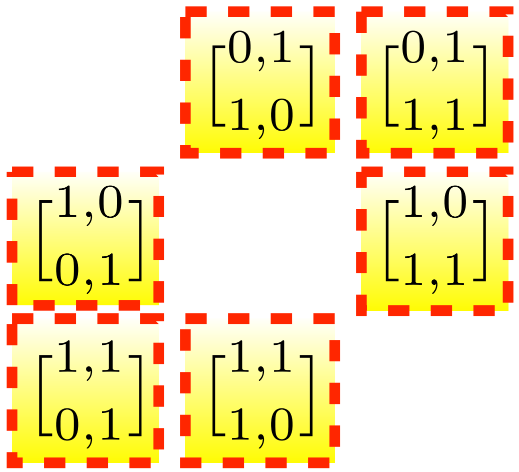
Z2 projected sub-sector

$$= \frac{1}{2} \times \int_{\mathcal{F}_0(2)} d\mu\; \Gamma_{2,2}\left[{0 \atop 1}\right](T,U)\, \frac{1}{2} \times \left(\begin{bmatrix}0,1\\1,0\end{bmatrix} + \begin{bmatrix}0,1\\1,1\end{bmatrix} \right)$$

highly non-holomorphic

Non-supersymmetric Universality

Spontaneous N=2 to N=0 non-BPS subsector



$$= \frac{1}{2} \times \int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\left[{0 \atop 1}\right](T,U)\, \frac{1}{2} \times \left(\left[{0,1 \atop 1,0}\right] + \left[{0,1 \atop 1,1}\right] \right)$$

$$\# \int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\left[{0 \atop 1}\right] \left\{ -\frac{\vartheta_2^8\, |\vartheta_3^4 + \vartheta_4^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} - \frac{\vartheta_2^4\, \vartheta_4^4\, |\vartheta_2^4 - \vartheta_4^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} + \frac{\vartheta_2^4\, \vartheta_3^4\, |\vartheta_2^4 + \vartheta_3^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} \right\}$$

highly non-holomorphic

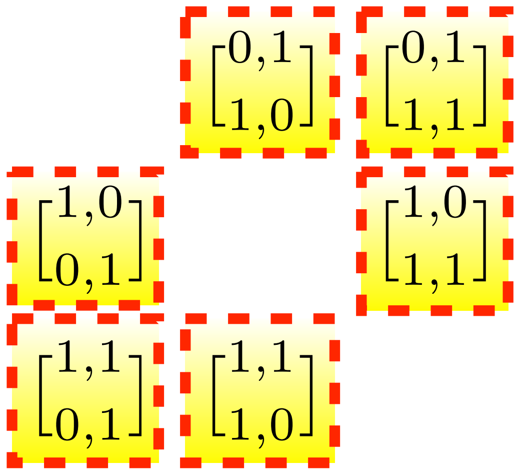
write in terms of Kac-Moody characters

$$12\, (O_8^2\, V_8 + 3V_8^3)\, (\bar O_8^2\, \bar V_8 - \bar V_8^3)$$

factorizes

Non-supersymmetric Universality

Spontaneous N=2 to N=0 non-BPS subsector



$$= \frac{1}{2} \times \int_{\mathcal{F}_0(2)} d\mu \; \Gamma_{2,2}\left[{}^{0}_{1}\right](T,U)\, \frac{1}{2} \times \left(\boxed{\begin{bmatrix} 0,1 \\ 1,0 \end{bmatrix}} + \boxed{\begin{bmatrix} 0,1 \\ 1,1 \end{bmatrix}} \right)$$

$$\# \int_{\mathcal{F}_0(2)} d\mu \; \Gamma_{2,2}\left[{}^{0}_{1}\right] \left\{ -\frac{\vartheta_2^8\, |\vartheta_3^4 + \vartheta_4^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} - \frac{\vartheta_2^4\, \vartheta_4^4\, |\vartheta_2^4 - \vartheta_4^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} + \frac{\vartheta_2^4\, \vartheta_3^4\, |\vartheta_2^4 + \vartheta_3^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} \right\}$$

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factorizes

Non-supersymmetric Universality

Spontaneous N=2 to N=0 non-BPS subsector

$$\begin{matrix} & \begin{bmatrix}0,1\\1,0\end{bmatrix} & \begin{bmatrix}0,1\\1,1\end{bmatrix} \\ \begin{bmatrix}1,0\\0,1\end{bmatrix} & & \begin{bmatrix}1,0\\1,1\end{bmatrix} \\ \begin{bmatrix}1,1\\0,1\end{bmatrix} & \begin{bmatrix}1,1\\1,0\end{bmatrix} & \end{matrix} = \frac{1}{2} \times \int_{\mathcal{F}_0(2)} d\mu \ \Gamma_{2,2}\left[{0 \atop 1}\right](T,U)\, \frac{1}{2} \times \left(\begin{bmatrix}0,1\\1,0\end{bmatrix} + \begin{bmatrix}0,1\\1,1\end{bmatrix} \right)$$

$$\# \int_{\mathcal{F}_0(2)} d\mu \ \Gamma_{2,2}\left[{0 \atop 1}\right] \left\{ -\frac{\vartheta_2^8\, |\vartheta_3^4 + \vartheta_4^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} - \frac{\vartheta_2^4\, \vartheta_4^4\, |\vartheta_2^4 - \vartheta_4^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} + \frac{\vartheta_2^4\, \vartheta_3^4\, |\vartheta_2^4 + \vartheta_3^4|^2\, \bar\vartheta_3^4\, \bar\vartheta_4^4}{\eta^{12}\, \bar\eta^{12}} \right\}$$

highly non-holomorphic

write in terms of Kac-Moody characters

$$12\,(O_8^2\, V_8 + 3V_8^3)\,\boxed{(\bar O_8^2\, \bar V_8 - \bar V_8^3)}$$

factorizes

$$= 8$$

Non-supersymmetric Universality

Spontaneous N=2 to N=0 non-BPS subsector

$$\begin{bmatrix}0,1\\1,0\end{bmatrix}\ \begin{bmatrix}0,1\\1,1\end{bmatrix}\ \begin{bmatrix}1,0\\0,1\end{bmatrix}\ \begin{bmatrix}1,0\\1,1\end{bmatrix}\ \begin{bmatrix}1,1\\0,1\end{bmatrix}\ \begin{bmatrix}1,1\\1,0\end{bmatrix} = \frac{1}{2}\times\int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\left[{0 \atop 1}\right](T,U)\,\frac{1}{2}\times\left(\begin{bmatrix}0,1\\1,0\end{bmatrix} + \begin{bmatrix}0,1\\1,1\end{bmatrix}\right)$$

$$\#\int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\left[{0 \atop 1}\right]\left\{-\frac{\vartheta_2^8\,|\vartheta_3^4+\vartheta_4^4|^2\,\bar\vartheta_3^4\,\bar\vartheta_4^4}{\eta^{12}\,\bar\eta^{12}} - \frac{\vartheta_2^4\,\vartheta_4^4\,|\vartheta_2^4-\vartheta_4^4|^2\,\bar\vartheta_3^4\,\bar\vartheta_4^4}{\eta^{12}\,\bar\eta^{12}} + \frac{\vartheta_2^4\,\vartheta_3^4\,|\vartheta_2^4+\vartheta_3^4|^2\,\bar\vartheta_3^4\,\bar\vartheta_4^4}{\eta^{12}\,\bar\eta^{12}}\right\}$$

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factorizes

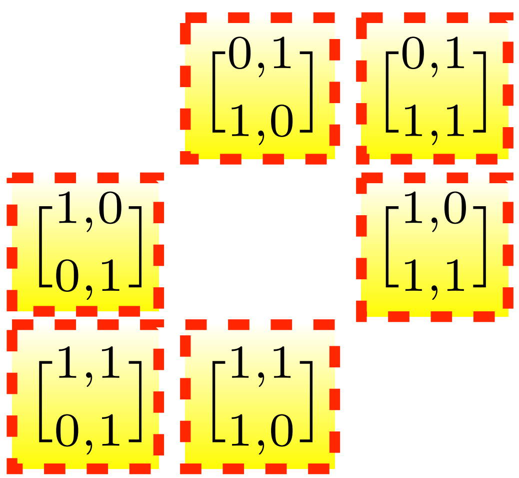
$$=8$$

MSDS identities

I.F. & Kounnas 2009

Non-supersymmetric Universality

Spontaneous N=2 to N=0 non-BPS subsector



$$= \frac{1}{2} \times \int_{\mathcal{F}_0(2)} d\mu \; \Gamma_{2,2}\left[{}^{0}_{1}\right](T,U) \, \frac{1}{2} \times \left(\begin{bmatrix} 0,1 \\ 1,0 \end{bmatrix} + \begin{bmatrix} 0,1 \\ 1,1 \end{bmatrix} \right)$$

$$\# \int_{\mathcal{F}_0(2)} d\mu \; \Gamma_{2,2}\left[{}^{0}_{1}\right] \left\{ - \frac{\vartheta_2^8 \, |\vartheta_3^4 + \vartheta_4^4|^2 \, \bar{\vartheta}_3^4 \, \bar{\vartheta}_4^4}{\eta^{12} \, \bar{\eta}^{12}} - \frac{\vartheta_2^4 \, \vartheta_4^4 \, |\vartheta_2^4 - \vartheta_4^4|^2 \, \bar{\vartheta}_3^4 \, \bar{\vartheta}_4^4}{\eta^{12} \, \bar{\eta}^{12}} + \frac{\vartheta_2^4 \, \vartheta_3^4 \, |\vartheta_2^4 + \vartheta_3^4|^2 \, \bar{\vartheta}_3^4 \, \bar{\vartheta}_4^4}{\eta^{12} \, \bar{\eta}^{12}} \right\}$$

highly non-holomorphic

$$= \frac{1}{2} \int_{\mathcal{F}_0(2)} d\mu \; \Gamma_{2,2}\left[{}^{0}_{1}\right](T,U) \left[\delta b + \delta b' \left(\frac{\vartheta_2(\tau)}{\eta(\tau)} \right)^{12} \right]$$

cancellations among the right moving oscillators !

$$\delta b = -\frac{32}{3} \qquad \delta b' = -\frac{2}{3}$$

hidden spectral flow

Non-supersymmetric Universality

a word about modular integrals

$$\int_{\mathcal{F}} d\mu\ \Gamma_{2,2}(T,U) = -\log T_2 U_2\, |\eta(T)\eta(U)|^4$$

$$\int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\left[{0 \atop 1}\right](T,U) = -\log T_2 U_2\, |\vartheta_4(T)\, \vartheta_2(U)|^4$$

generalization

$$\int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}(T,U)\, j(\tau) = -\log |j(T) - j(U)|^2$$

$$\int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\left[{0 \atop 1}\right](T,U)\, \frac{\vartheta_2^{12}}{\eta^{12}} = -2\log |j_2(T/2) - j_2(U)|^4$$

new result

based on a generalized Borcherds product formula for $\Gamma_0(2)$

$$\prod_{\substack{K>0 \\ L\in\mathbb{Z}}} \left(\frac{(1-q_T^K\, q_U^L)^N}{1-q_T^{NK}\, q_U^{NL}} \right)^{c(KL)} = \left(\frac{j_2(T) - j_2(U)}{j_2(T) - 24} \right)^2$$

$$\frac{\vartheta_2^{12}}{\eta^{12}} + 24 = \sum_n c(n)\, q^n$$

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Angelantonj, I.F. , Pioline 2015

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Non-supersymmetric Universality

Full Result for $\mathrm{K3} \sim T^4/\mathbb{Z}_2$

$$\Delta_{\mathrm{SO}(16)} - \Delta_{\mathrm{SO}(12)} = 72\,\log[T_2 U_2\,|\eta(T)\,\eta(U)|^4] - \frac{8}{3}\,\log[T_2 U_2\,|\vartheta_4(T)\,\vartheta_2(U)|^4] + \frac{2}{3}\,\log|j_2(T/2) - j_2(U)|^4$$

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$$j_2(\tau) = \left(\frac{\eta(\tau)}{\eta(2\tau)}\right)^{24} + 24$$

Non-supersymmetric Universality

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$$(\alpha,\beta,\gamma) = (72, -\tfrac{8}{3}, \tfrac{2}{3}) \qquad \mathbb{Z}_2 \;\&\; \mathbb{Z}_3$$

$$(\alpha,\beta,\gamma) = \tfrac{5}{8}(72, -\tfrac{8}{3}, \tfrac{16}{15}) \qquad \mathbb{Z}_4$$

$$(\alpha,\beta,\gamma) = \tfrac{35}{144}(72, -\tfrac{8}{3}, \tfrac{1}{3}) \qquad \mathbb{Z}_6$$

Independently of the details of the vacuum (almost)

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logarithmic singularity at $T/2 = U$ (plus images)

extra charged massless states

Drastically different than the supersymmetric case

Non-supersymmetric Universality

Full Result for $\mathrm{K3} \sim T^4/\mathbb{Z}_N$

difference of beta function coefficients

$$\Delta_{\mathrm{SO}(16)} - \Delta_{\mathrm{SO}(12)} = \alpha \log[T_2 U_2 \, |\eta(T)\, \eta(U)|^4] + \beta \log[T_2 U_2 \, |\vartheta_4(T)\, \vartheta_2(U)|^4] + \gamma \log |j_2(T/2) - j_2(U)|^4$$

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jump in beta function coefficients

Non-supersymmetric Universality

What is the origin of this unexpected universality ?

$$\frac{16\pi^2}{g_i^2} = \int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\big[{0 \atop 1}\big] \sum_g \frac{\mathcal{L}\big[{0,1 \atop 1,g}\big]}{\eta^2\, \vartheta\big[{0 \atop 1+g}\big]\, \vartheta\big[{0 \atop 1-g}\big]} \times \frac{\Phi_i\big[{0,1 \atop 1,g}\big]}{\bar\eta^{18}\, \bar\vartheta\big[{0 \atop 1+g}\big]\, \bar\vartheta\big[{0 \atop 1-g}\big]}$$

helicity supertrace — group trace

$$\Delta\Phi\big[{H,h \atop G,g}\big] = \frac{i}{8\pi} \sum_{k,\ell,\rho,\sigma\in\mathbb{Z}_2} (-)^{(k+\rho)G+(\ell+\sigma)H}\ \bar\vartheta\big[{k \atop \ell}\big]^6\ \bar\vartheta\big[{k+h \atop \ell+g}\big]\ \bar\vartheta\big[{k-h \atop \ell-g}\big]\ \bar\vartheta\big[{\rho \atop \sigma}\big]^8\ \partial_{\bar\tau} \log \frac{\bar\vartheta\big[{\rho \atop \sigma}\big]}{\bar\vartheta\big[{k \atop \ell}\big]}$$

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spectral flow
(repeated Riemann identities)

$$= 4\left(2(-1)^{(1+H)(1+G)} - 1\right) \bar\eta^{18}\, \bar\vartheta[^{1+h}_{1+g}]\, \bar\vartheta[^{1-h}_{1-g}]\,.$$

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left-right "mirror" of BPS property : projects on right-moving ground states !

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$$= \alpha + \beta \, \frac{\vartheta_2^{12}}{\eta^{12}}$$

= constant

constrained by holomorphy and modularity

Universality : special property of "N=2 sectors"

depends on the orbifold action on the bosonic side of the heterotic string

CERN

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Suppose that SUSY could be restored : $(-1)^{F_{\rm s.t.}} (-1)^{F_1+F_2}\, \delta \to (-1)^{F_1+F_2}\, \delta$

the left-moving contribution drops out

IF there is no (vector/hyper) enhancement in the bulk of T,U

$$\frac{\delta\Phi\left[{0,1 \atop 1,g}\right]}{\bar\eta^{18}\, \bar\vartheta\left[{0 \atop 1+g}\right]^2} = \text{constant}$$

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= constant

constrained by holomorphy and modularity

What if there is (vector/hyper) enhancement ?

$$\frac{\delta\Phi\left[{}^{0,1}_{1,g}\right]}{\bar\eta^{18}\, \bar\vartheta\left[{}^{\ 0}_{1+g}\right]^2} = \kappa + \lambda (-1)^g\, \frac{\bar\vartheta\left[{}^{\ 0}_{1+g}\right]^{12}}{\bar\eta^{12}}$$

reflects the presence of extra massless states

Additional contributions to the thresholds : generalised universality

$$\int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\left[{}^0_1\right] \left|\frac{\vartheta_2^{12}}{\eta^{12}}\right|^2 + \int_{\mathcal{F}_0(2)} d\mu\ \Gamma_{2,2}\left[{}^0_1\right] \left|\frac{E_6 + E_4 X_2}{\eta^{12}}\right|^2$$

Universality in Models with Chirality

Does non-supersymmetric Universality arise in chiral models ?

What about singularities due to extra massless scalars ?

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Work with CY in the singular limit realised as $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ with standard embedding

$$G = \mathrm{E}_6 \times \mathrm{E}_8 \times \mathrm{U}(1)^2$$

Charged massless spectrum : Chiral

g_1 - twisted sector	16 chiral multiplets in $(\mathbf{27}, \mathbf{1}) + (1, 1)$
g_2 - twisted sector	16 chiral multiplets in $(\mathbf{27}, \mathbf{1}) + (1, 1)$
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Turn on a Scherk-Schwarz flux on top $\mathbb{Z}_2' = (-1)^{F_{\rm s.t.}+F_1+F_2}\,\delta$

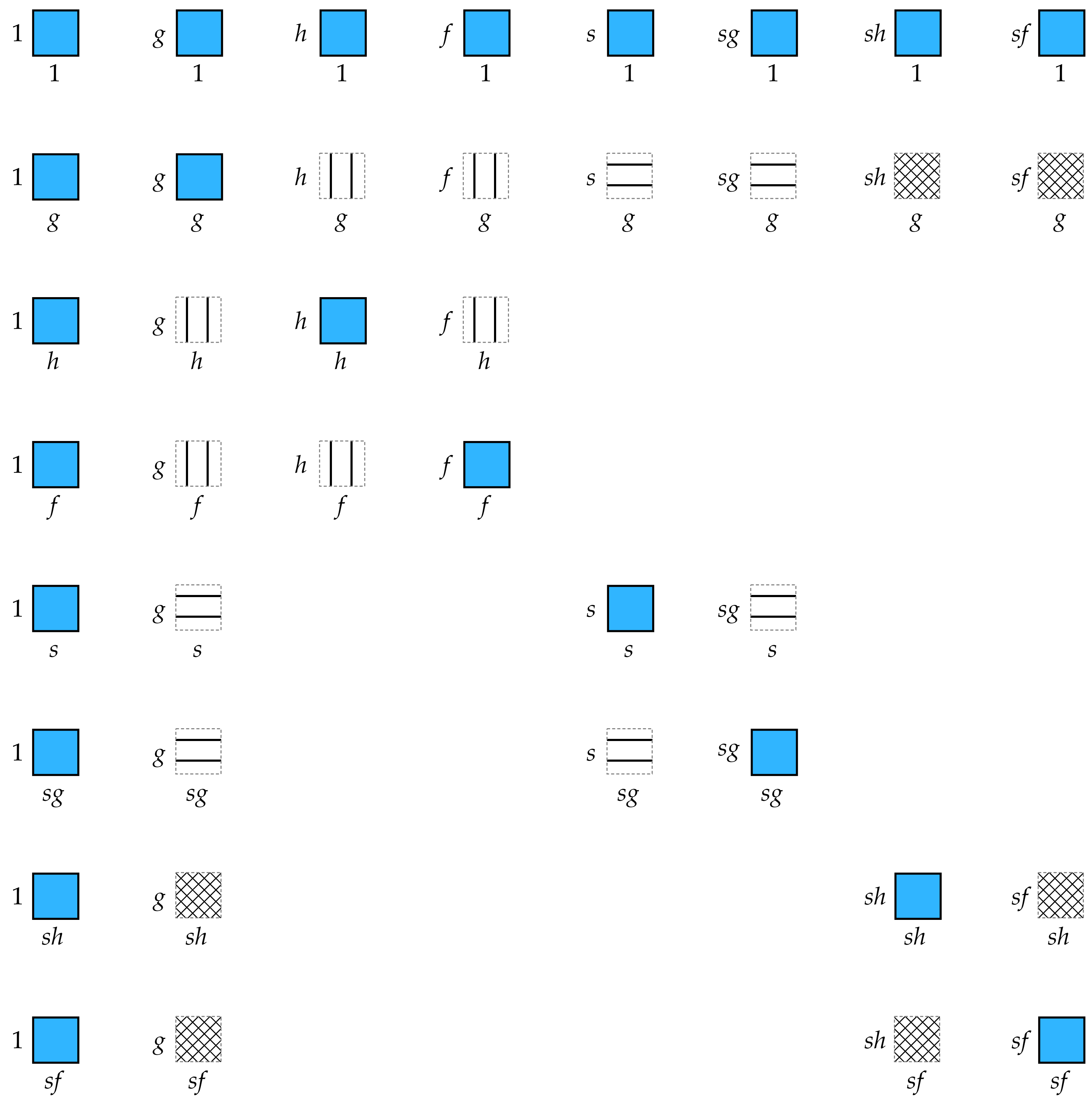
Universality in Models with Chirality

$G = \mathrm{SO}(10) \times \mathrm{SO}(16)$ CY with Scherk-Schwarz flux (N=0)

Charged massless spectrum : Chiral

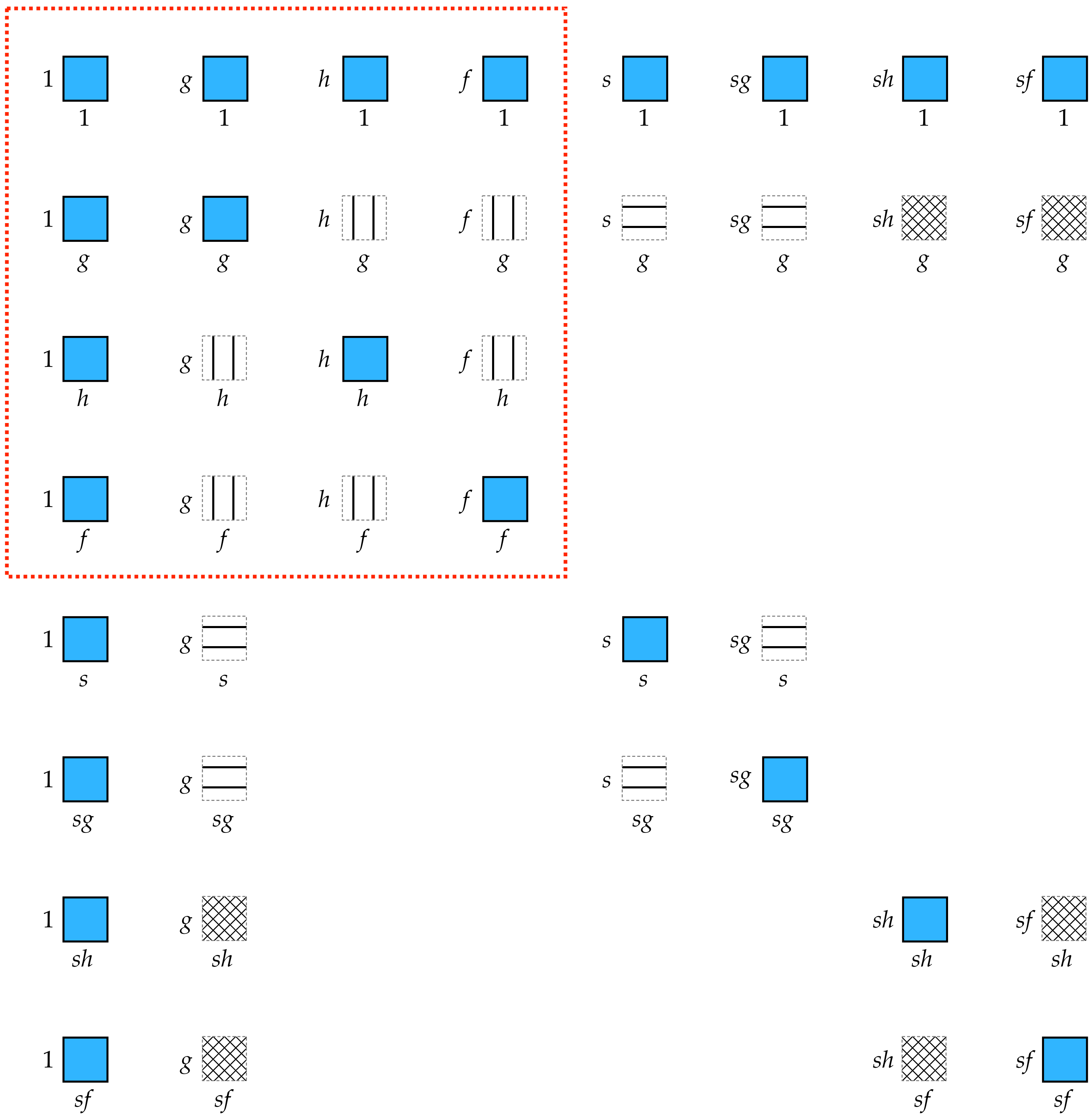
twisted sectors	16 N=1 chiral multiplets	$(\mathbf{16}, \mathbf{1}) + (\mathbf{10}, \mathbf{1}) + (\mathbf{1}, \mathbf{1})$
	16 complex scalars	$(\mathbf{10}, \mathbf{1}) + 2(\mathbf{1}, \mathbf{1})$
	16 fermions	$(\mathbf{16}, \mathbf{1})$

Universality in Models with Chirality



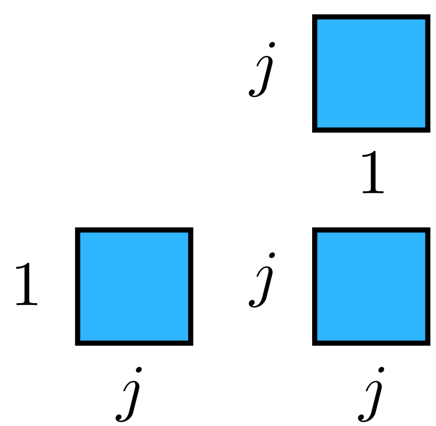
Universality in Models with Chirality

$Z_2 x Z_2$



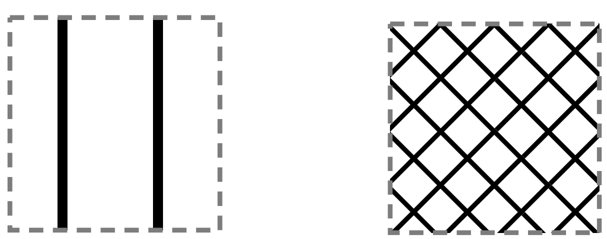
Universality in Models with Chirality

"Blue orbits"

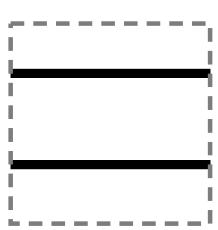


$$-\log T_2^{(i)} U_2^{(i)} \, |\eta(T^{(i)})\, \eta(U^{(i)})|^4$$

$$-\log T_2^{(1)} U_2^{(1)} \, |\vartheta_4(T^{(1)})\, \vartheta_2(U^{(1)})|^4$$



topological orbits



truly non-BPS orbit

identical to the non-BPS orbit of the prototype model !

$$-\log \left| j_2(T^{(1)}/2) - j_2(U^{(1)}) \right|^4$$

universality

Conclusions

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- ☑ Opens possibilities for string model building

Outlook

Outlook

☑ Gravitational thresholds

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- ☑ Gravitational thresholds
- ☑ Semi-realistic string model building ?

Thank you !