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Orbifolds as Free Fermion Models

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String Model Building
The Heterotic String

- Closed string theory
- Synthesis of bosonic string and superstring
- Particle phenomenology widely explored - most realistic string theory? Ohio, Pennsylvania, Oxford, Liverpool, Munich, Bonn,...
- Many descriptions
    - Effective constructions
    - Worldsheet constructions

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Orbifolds

Free fermions

Orbifolds and Free Fermions

History

- Since Antoniadis-Bachas-Kounnas/Kawai-Lewellen-Tye `87 (FFF) and Dixon-Harvey-Vafa-Witten `85 (Orbifolds), worldsheet constructions have been widely explored

- Previous works have discussed a correspondence
    - Including Kounnas-Kiritsis `97, Donagi-Wendland `08,...

- However, model builder's dictionary still missing...
    - Computational comparison currently inaccessible!

Orbifolds

- Described by worldsheet bosonic degrees of freedom
- $X^{\mu,i}$ and $\tilde{X}^{I}$ describe 10D spacetime and internal T^{16}
- Limited to gauge groups of rank-16

Orbifolds

Model Building Tools

- Ingredients:
  - Point group $\longrightarrow \theta$ (discrete identifications)
  - Space group $\longrightarrow g$ (θ + lattice vector)
  - Gauge embedding
    - Shift vectors $\longrightarrow V$
    - Wilson lines $\longrightarrow A$

Free Fermion Construction

hidden gauge group generators

superpartners of X^μ

$$\psi^{\mu}, \chi^{i}, \overbrace{y^{i}, w^{i} | \overline{y}^{i}, \overline{w}^{i}}^{\text{“compactified” directions}}, \overline{\psi}^{1,\dots,5}, \overline{\eta}^{1,2,3}, \overline{\phi}^{1,\dots,8}$$

visible gauge group generators

superpartners of compactification bosons

Free Fermion Construction

Model Building tools

- Fermion boundary condition basis vectors $\mathbf{b}_i$

$$\alpha \in \Xi \sim \mathbb{Z}_2 \oplus \mathbb{Z}_2 \oplus \dots$$

- GSO projections

$$\left\{ e^{i\pi(\mathbf{b}_i \cdot F_\alpha)} - \delta_\alpha c^* \begin{pmatrix} \alpha \\ \mathbf{b}_i \end{pmatrix} \right\} |s\rangle_\alpha = 0$$

- Fermions may be real or complex

- As with bosons, real fermion pairs may be complexified

Fermionization/Bosonization

- In 2D, known relationship between real bosons/fermions

$$y + iw =: e^{iX} :$$

- Relate boundary conditions of compactified dimensions:

Fermion	Boson	
$\{y, w\} \to -\{y, w\}$	$X \to X + \pi$	"shift"
$\{y, w\} \to \{y, -w\}$	$X \to -X$	"twist"
$\{y, w\} \to \{-y, w\}$	$X \to -X + \pi$	"roto-translation"

up to lattice vector...

Comparison

Worked example - The Extended NAHE set

Fermions that appear are periodic *i.e.* do not transform

$$\mathbb{1} = \{\mathrm{ALL}\}$$

$$\mathbf{S} = \{\psi^\mu, \chi^{1,\dots,6}\}$$

$$\mathbf{x} = \{\psi^{1,\dots,5}, \eta^{1,2,3}\}$$

$$\mathbf{b}_1 = \left\{\psi^\mu, \chi^{12}, y^{3,\dots,6} \,|\, \overline{y}^{3,\dots,6}, \overline{\psi}^{1,\dots,5}, \overline{\eta}^1\right\}$$

$$\mathbf{b}_2 = \left\{\psi^\mu, \chi^{34}, y^{1,2}, w^{5,6} \,|\, \overline{y}^{1,2}, \overline{w}^{5,6}, \overline{\psi}^{1,\dots,5}, \overline{\eta}^2\right\}$$

$$\mathbf{b}_3 = \left\{\psi^\mu, \chi^{56}, w^{1,\dots,4} \,|\, \overline{w}^{1,\dots,4}, \overline{\psi}^{1,\dots,5}, \overline{\eta}^3\right\}$$

$$\Rightarrow E_6 \times U(1)^2 \times E_8 \times SO(4)^3$$

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Comparison

Worked example - The Extended NAHE set

- First basis vectors $\mathbb{1}$ and $\mathbf{S}$ correspond to $g = (\mathbb{1}, 0)$ with left spin structures identified
- $\mathbb{Z}_2$ orbifold action in $X^{3,\ldots,6}$ corresponds to $\mathbf{b}_1$
- In fact, $\mathbf{b}_1$, $\mathbf{b}_2$ and $\mathbf{b}_3$ corresponds to $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifolding
- These basis vectors thought to give "standard embedding"
  - BUT ONLY 24 GENERATIONS!! (Fixed points)

Comparison

Worked example - The Extended NAHE set

$$\frac{T^6}{\mathbb{Z}_2 \times \mathbb{Z}_2}$$

48 fixed points

$$\frac{SO(12)}{\mathbb{Z}_2 \times \mathbb{Z}_2}$$

24 fixed points

- Geometrical backgrounds are different
- At fermionic point, lattice always “non-standard”?

Conclusions and Outlook

- Correspondence between $\mathbb{Z}_2 \times \mathbb{Z}_2$ “standard” embeddings
- Shifts, twists and roto-translations identified
- Compactification lattices *always* enhanced?
- Partition functions matched
- Significant rewriting of available code currently underway...

Danke für Ihre Aufmerksamkeit!