Exploring The String Theory Landscape

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Early String Theory Expectations: (≈ 1985)

"*The hope is that the constraints imposed on such theories solely by the need for mathematical consistency are so strong that they essentially determine a single possible theory uniquely, and that by working out the consequences of the theory in detail one might eventually be able to show that there must be particles with precisely the masses, interactions, and so on, of the known elementary particles: in other words, that the world we live in is the only possible one.*"

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From "The Problems of Physics" by Antony Legget (1987)

A.N. Schellekens,
Contribution to the proceedings of the EPS conference, Uppsala, June 1987

The prevailing attitude seems to be that "non-perturbative string effects" will somehow select a unique vacuum. This is unreasonable and unnecessary wishful thinking. We do not know at present how to discuss such effects, and have no idea whether they impose any restrictions at all. One cannot reasonably expect that a mathematical condition will have a unique solution corresponding to the standard model with three generations and a bizarre mass matrix. It is important to realize that this quest for uniqueness is based on philosophy, not on physics. There is no logical reason why the "theory of everything" should have a unique vacuum.

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A. Strominger (1986)

All of this points to the overwhelming need to find a dynamical principle for determining the ground state, which now appears more imperative than ever.

String Theory and the Standard Model

- String theory is a candidate theory of quantum gravity.
- In string theory, gravity is mediated by exchange of loops of closed strings.
- Only couples to matter that is also made out of strings.
- Hence the Standard Model and everything else must be made out of strings as well.
- But nothing suggests that this should be unique.

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$$\mathcal{N}_{vac} \sim \frac{(2\pi L)^{K/2}}{(K/2)!}[c_n]$$

Typical $K \sim 100-400$ and $L \sim 500-5000$, leading to $\mathcal{N}_{vac} \sim 10^{500}$.

... but this does not mean that *any* QFT can be obtained.

It also does not mean that the Standard Model is nothing more than a random choice from a huge ensemble.

There is structure in the Standard Model, and there is structure in the string theory Landscape.

for more, see: **The Emperor's Last Clothes?**

Rept. Prog. Phys. 71:072201,2008. (20 pages) Extended version: **arXiv:0807.3249 (87 pages)**

Embedding the Standard Model

There are a priori two* basic classes:

1. Standard model from closed strings

2. Standard model from open strings

In both cases, gravity comes from closed strings

(*) Exact perturbative string realizations, not including *e.g*. F-theory

Embedding the Standard Model

Remarkably, in both cases the gross features of the Standard Model come out very easily

1. Standard model from closed strings:

   Heterotic strings naturally lead to a number of (16)'s of SO(10).

2. Standard model from open strings:

   Three classes of intersecting brane realizations.

But in all cases some details are problematic.

Some basic string theory

Polyakov action:

$$S[X,\gamma] = -\frac{1}{4\pi\alpha'}\int d\sigma d\tau \sqrt{-\det\gamma}\sum_{\alpha\beta}\gamma^{\alpha\beta}\partial_\alpha X^\mu \partial_\beta X_\mu$$

$X^\mu(\sigma,\tau)$ defines the embedding of the string in space-time.

$(\mu = 0,\ldots,D-1)$ Only consistent if D=26.

This can be overcome by replacing part of the action by a more general conformal field theory.
Such a CFT provides a representation of the Virasoro algebra.

Virasoro algebra:

$$[L_m, L_n] = (m-n)L_{m+n} + \frac{1}{12}c(m^3 - m)\delta_{m+n}$$

The constant c measures the contribution of a term in the action. It is additive, and has to add up to 26.

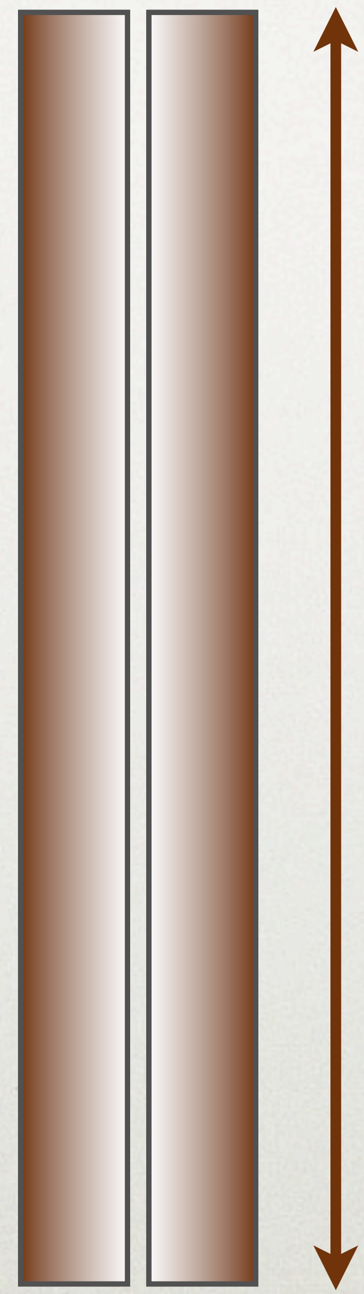
Typically, the theory is build out of some simple building blocks, in order to get some computational control.

In closed strings, there are separate algebras for left-moving and right-moving modes.

One may build the left-moving sector and the right-moving separately out of different building blocks.

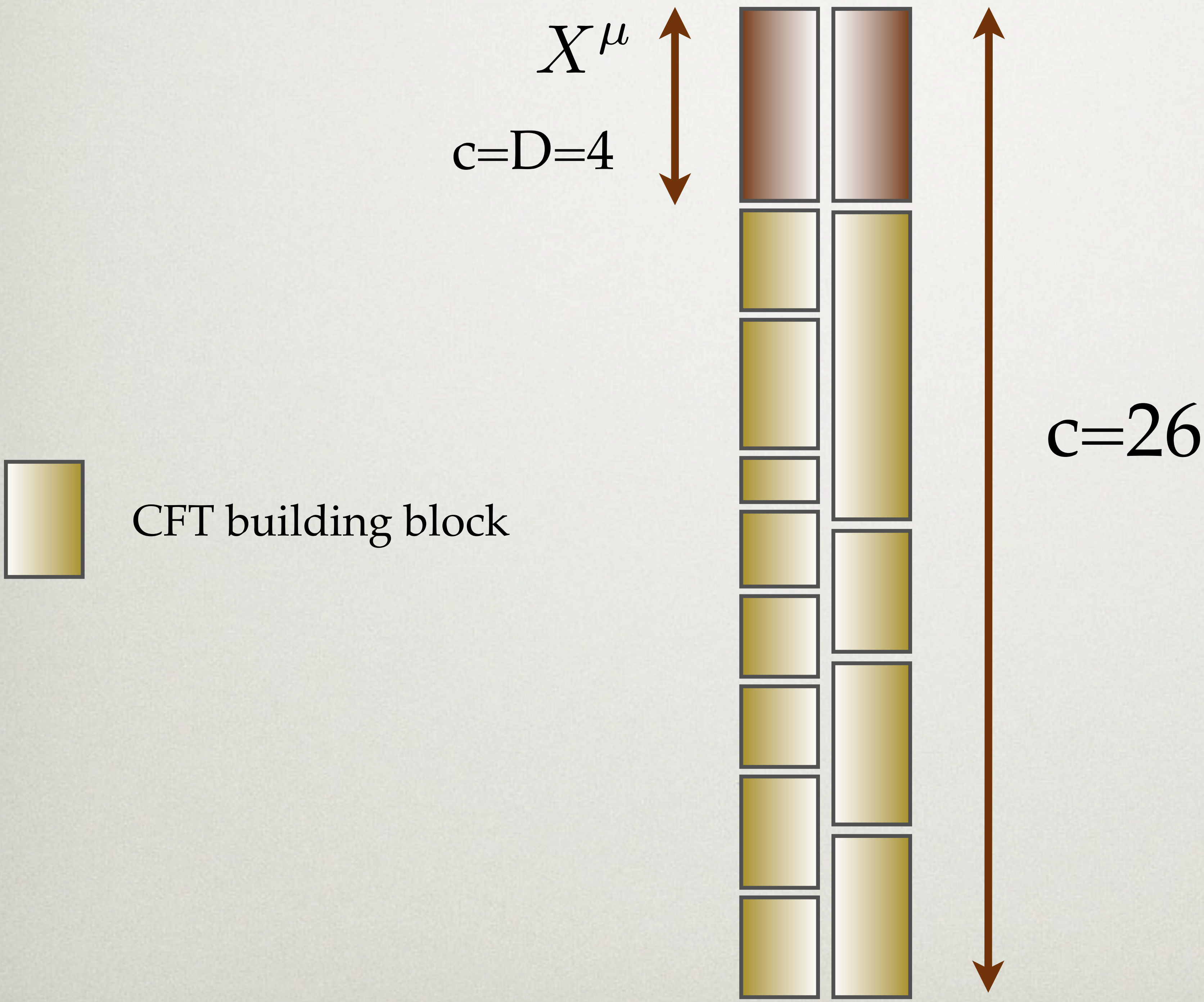
Basic Bosonic String

X^{μ}



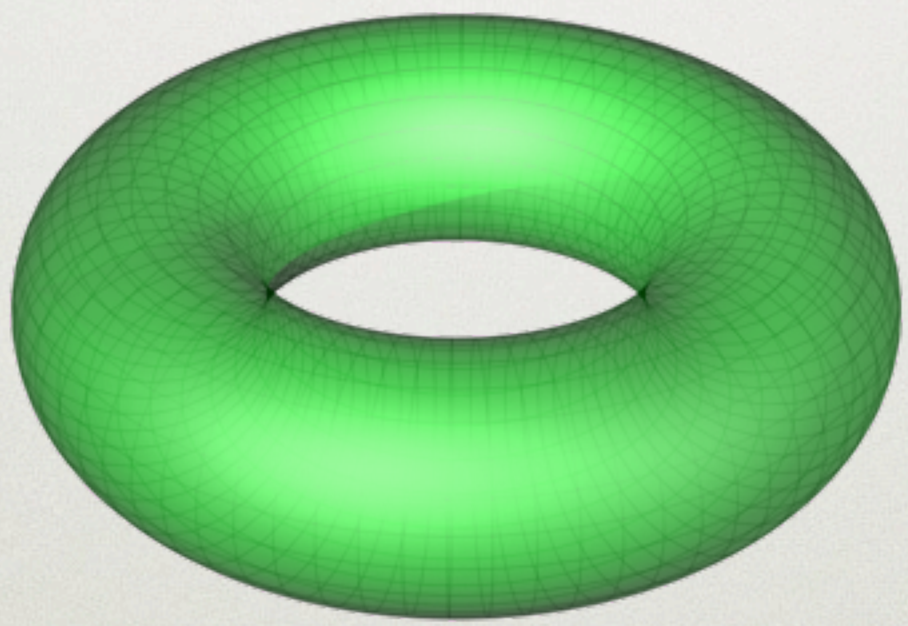
c=26

Compactified Bosonic String



Modular invariance

The freedom of associating left and right building blocks is severely limited by a constraint arising from the consistency of the simplest one-loop diagram, the torus.



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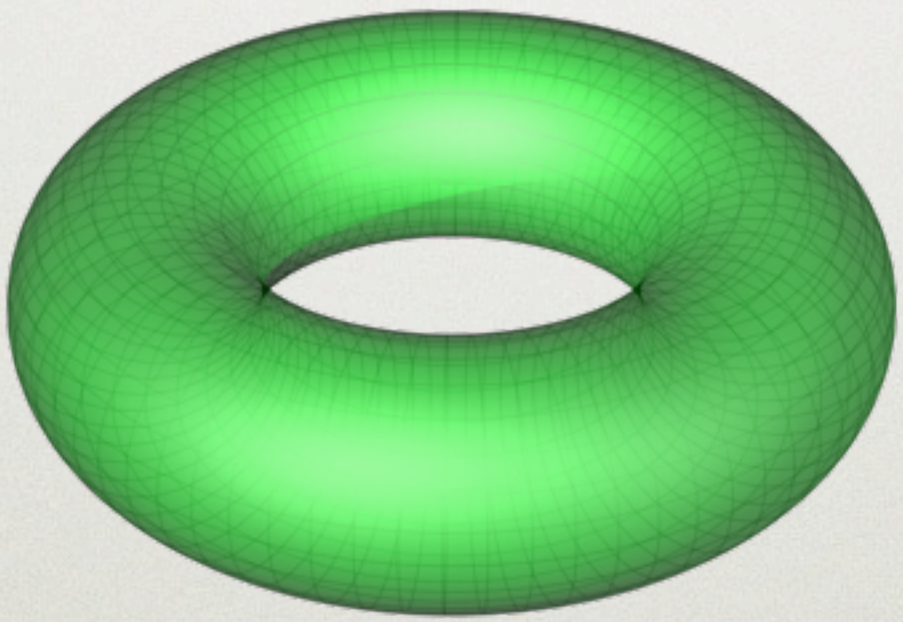

Modular invariance

Integrand must be invariant under $\begin{cases} \tau \to \tau + 1 & \text{T} \\ \tau \to -\dfrac{1}{\tau} & \text{S} \end{cases}$

$$\tau \to \frac{a\tau + b}{c\tau + d}, \qquad a, b, c, d \in \mathbf{Z}; \quad ad - bc = 1$$

Modular invariance

$$\int \frac{d^2\tau}{(\mathrm{Im}\tau)^{D/2+1}}\ \mathrm{Tr}\ e^{-\mathrm{Im}\tau H}$$

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$$\tau \to \frac{a\tau + b}{c\tau + d}, \qquad a, b, c, d \in \mathbf{Z}; \quad ad - bc = 1$$

Modular invariance

The integrand can be expressed in terms of Virasoro characters

$$\chi_i = \mathrm{Tr}_i \; e^{2\pi i(L_0 - c/24)}$$

Then the integrand is

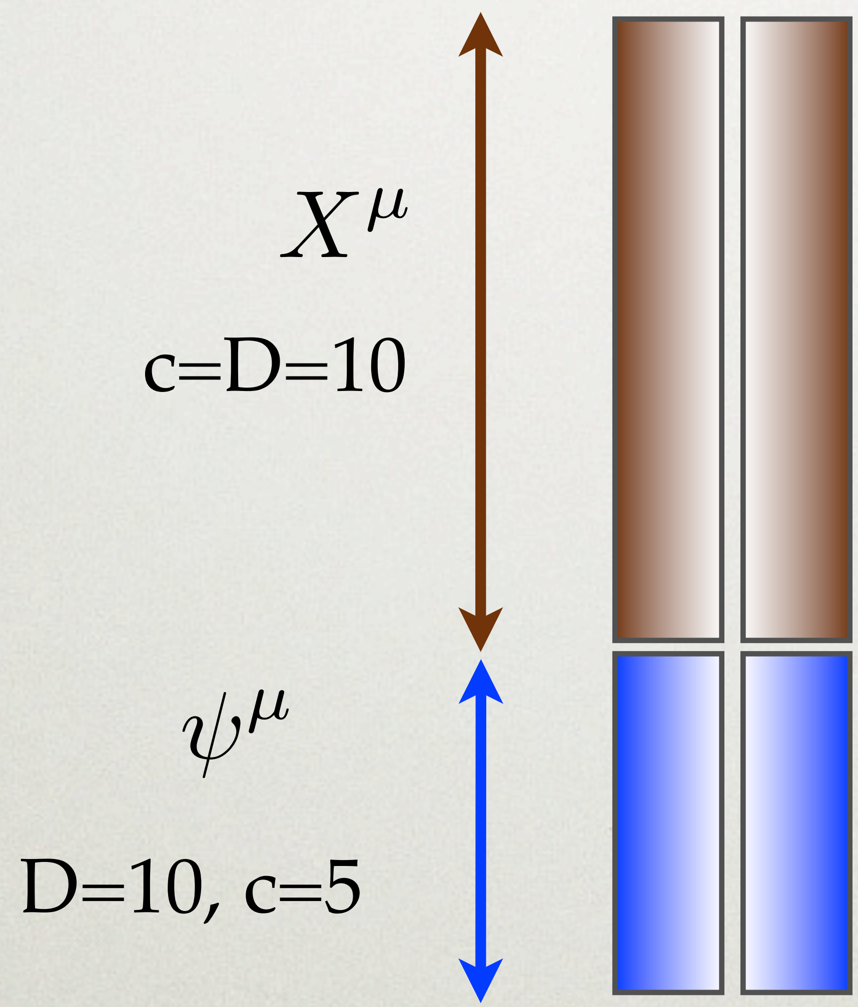
$$P(\tau, \bar{\tau}) = \sum_{ij} \chi_i(\tau) M_{ij} \xi_j(\bar{\tau})$$

In this formulation, modular invariance reduces to the condition

$$[M, T] = [M, S] = 0$$

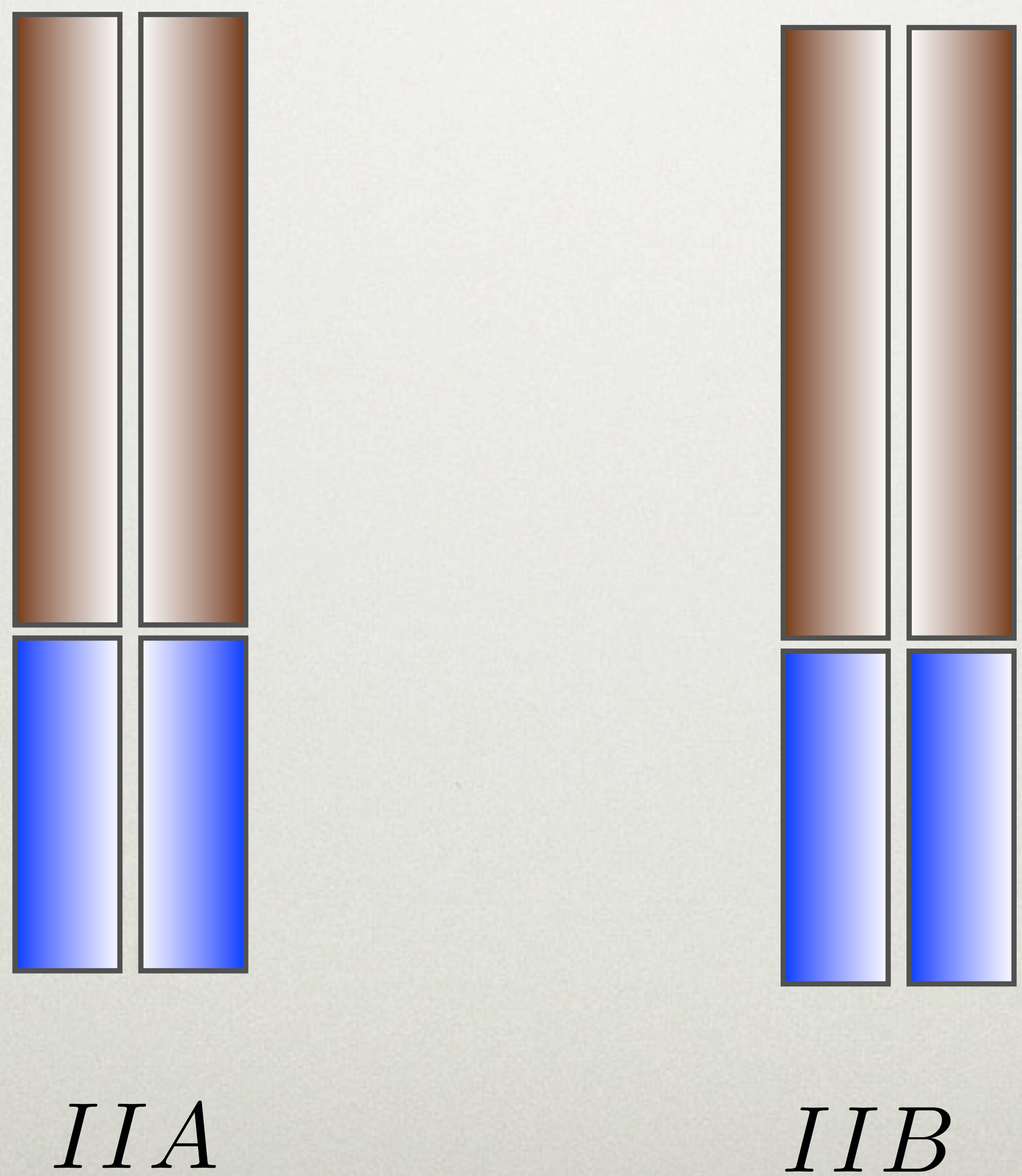
Canonical solution: $M_{ij} = \delta_{ij}$

Fermionic Strings

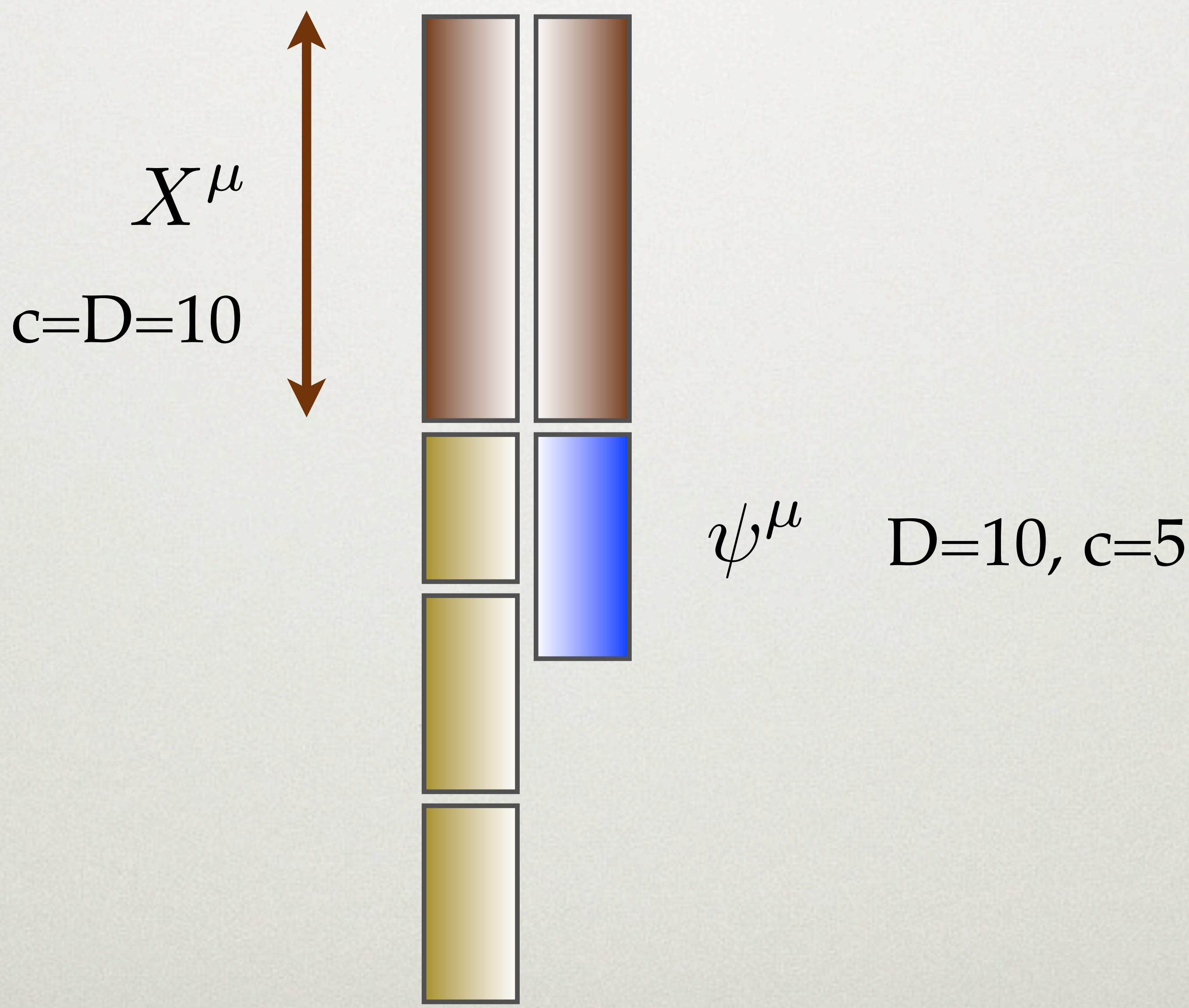


Fermionic Strings

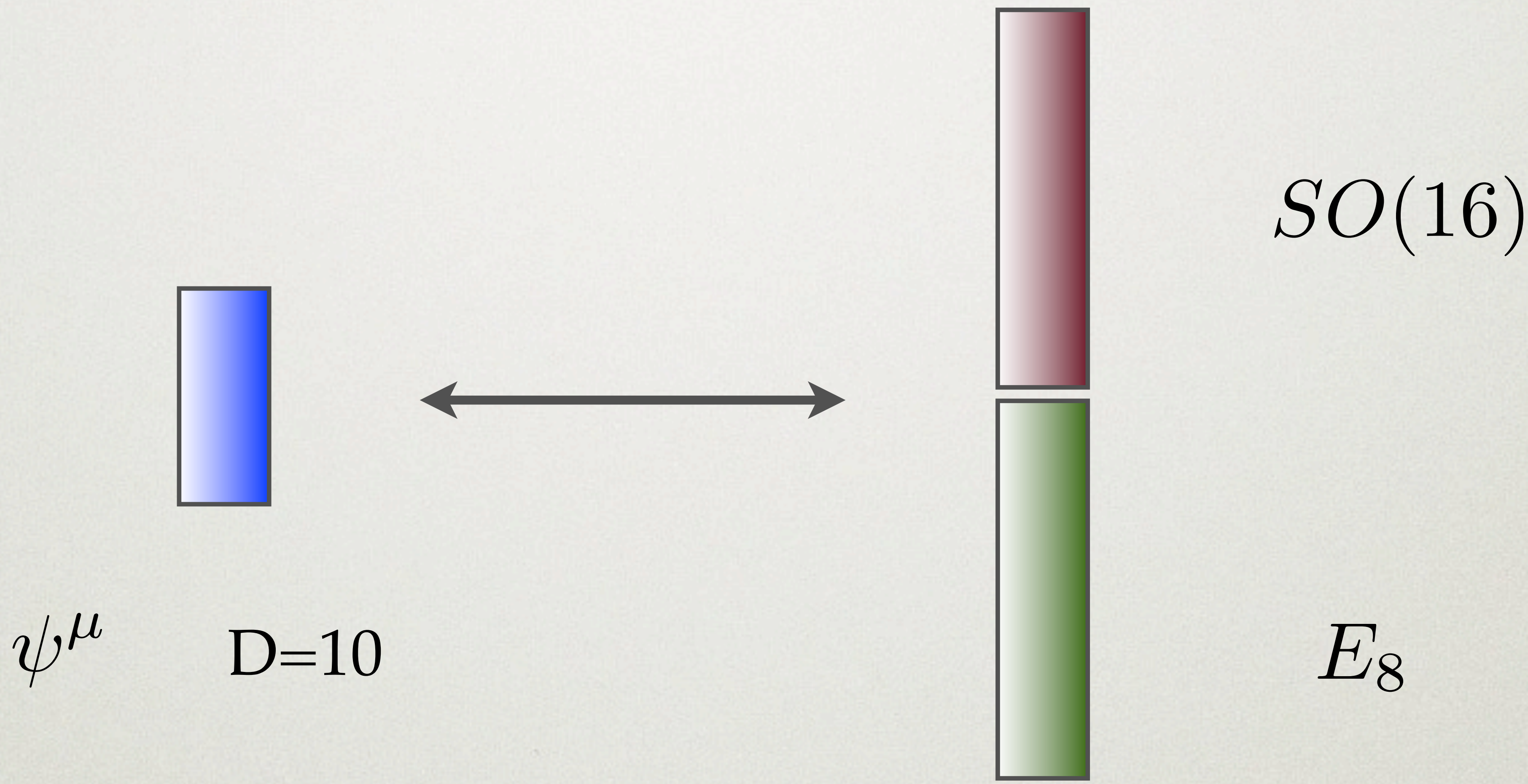
Modular invariance allows two solutions



Heterotic strings

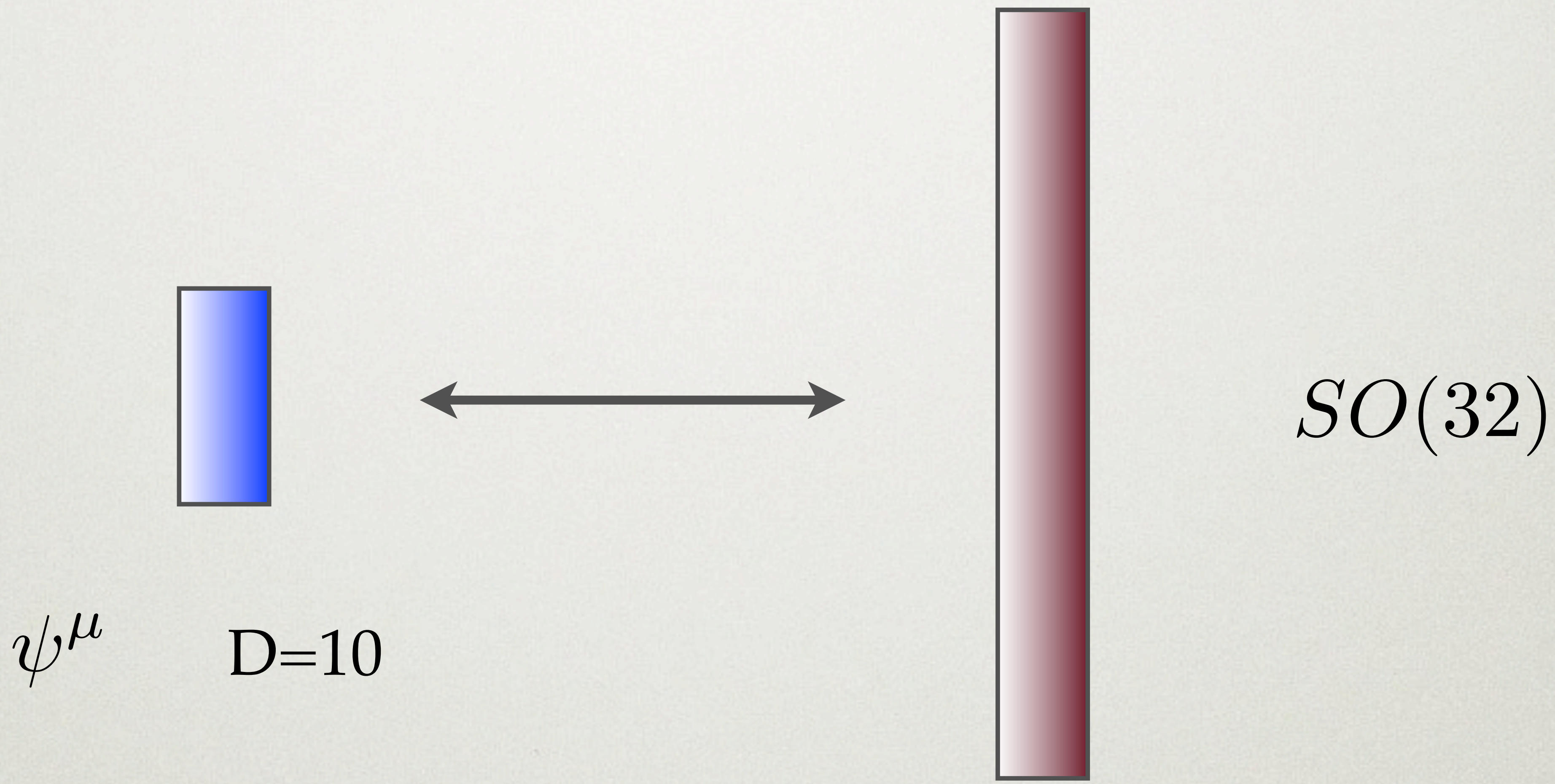


Modular invariance restricts this severely. Solutions exist because of isomorphisms between modular group representations.



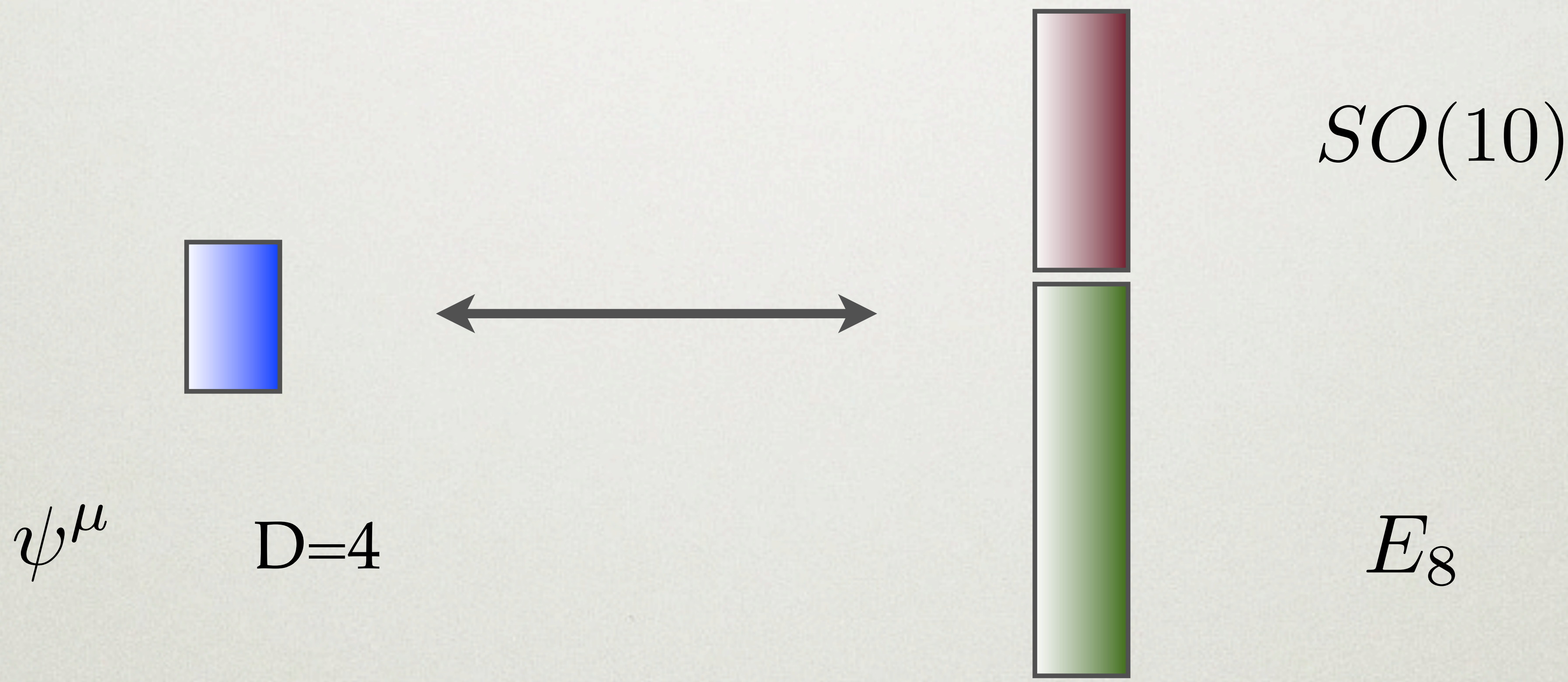
$SO(16)$, E_8 are special CFT building blocks called affine Lie algebras. They appear in the spectrum as gauge symmetries

Another solution:



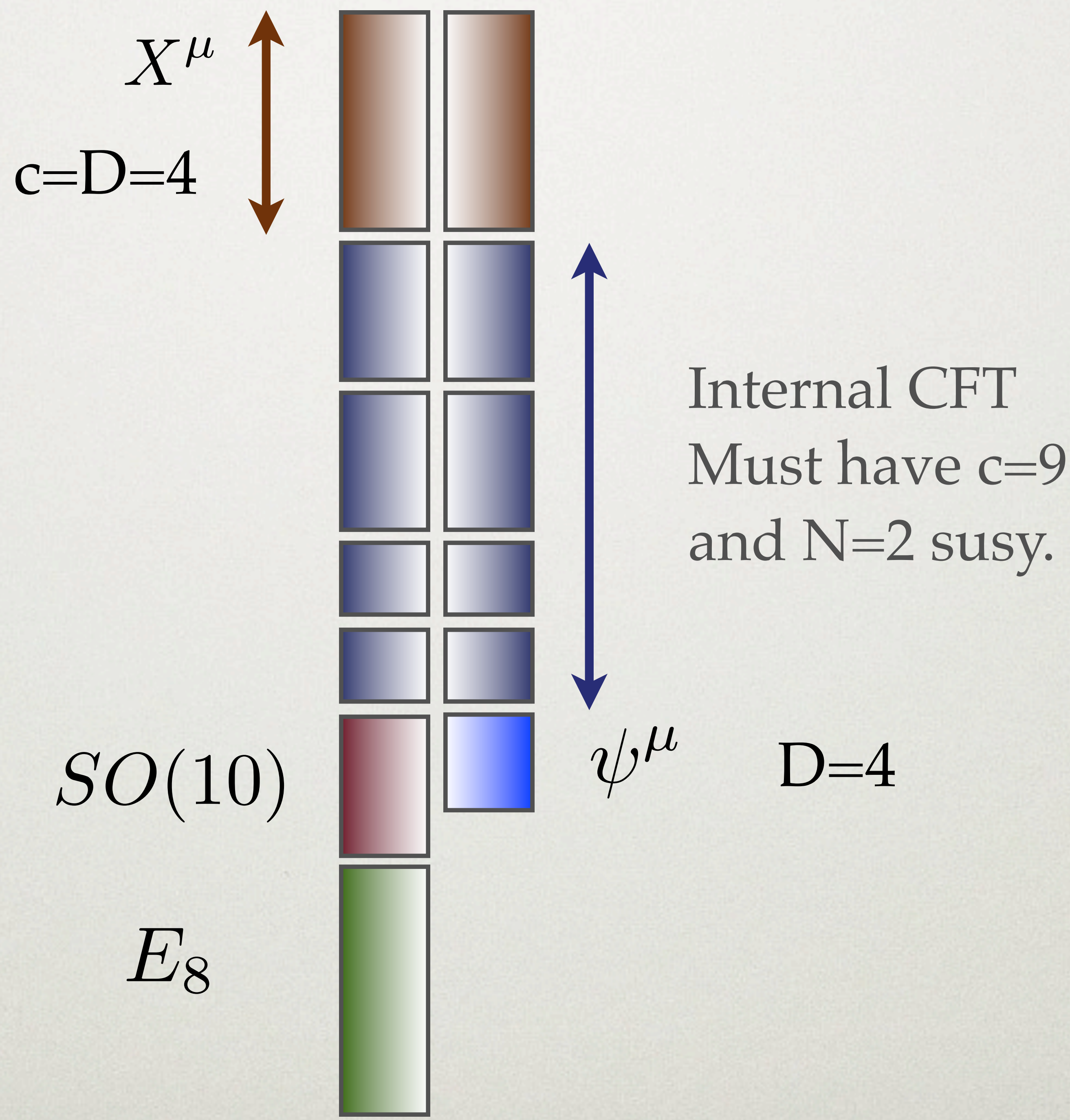
The Bosonic String Map

This also works in 4 dimensions:



Lerche, Lüst, Schellekens (1986)

Now we can build 4-dimensional strings



The resulting 4D strings have gauge bosons of the GUT group SO(10) (× E_8). Furthermore the bosonic string map guarantees that massless, chiral matter consists of a certain number of families in the (16) of SO(10).

A (perhaps) more familiar statement is that string theory "naturally" gives rise to (27)'s of E_6. This follows from "Calabi-Yau" compactification*, and is a special case of the bosonic string map with the simplest realization of space-time supersymmetry.

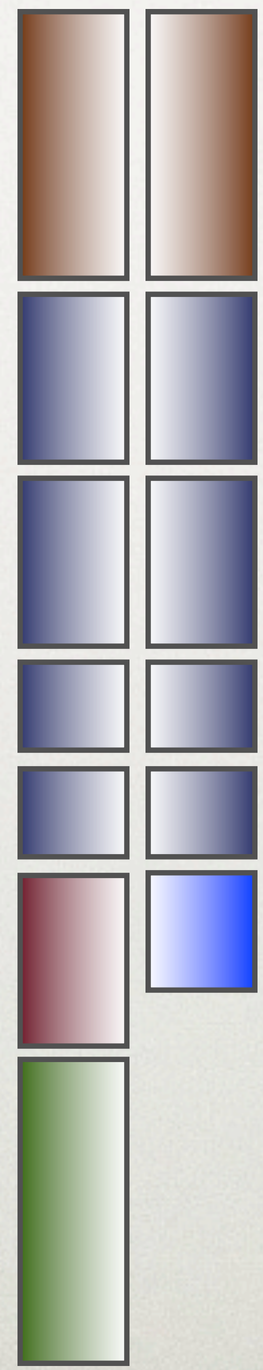
(*) Candelas, Horowitz, Strominger, Witten (1984)

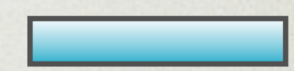
Imposing space-time supersymmetry

Required by
modular invariance.
Extends SO(10) to E_6

$SO(10)$

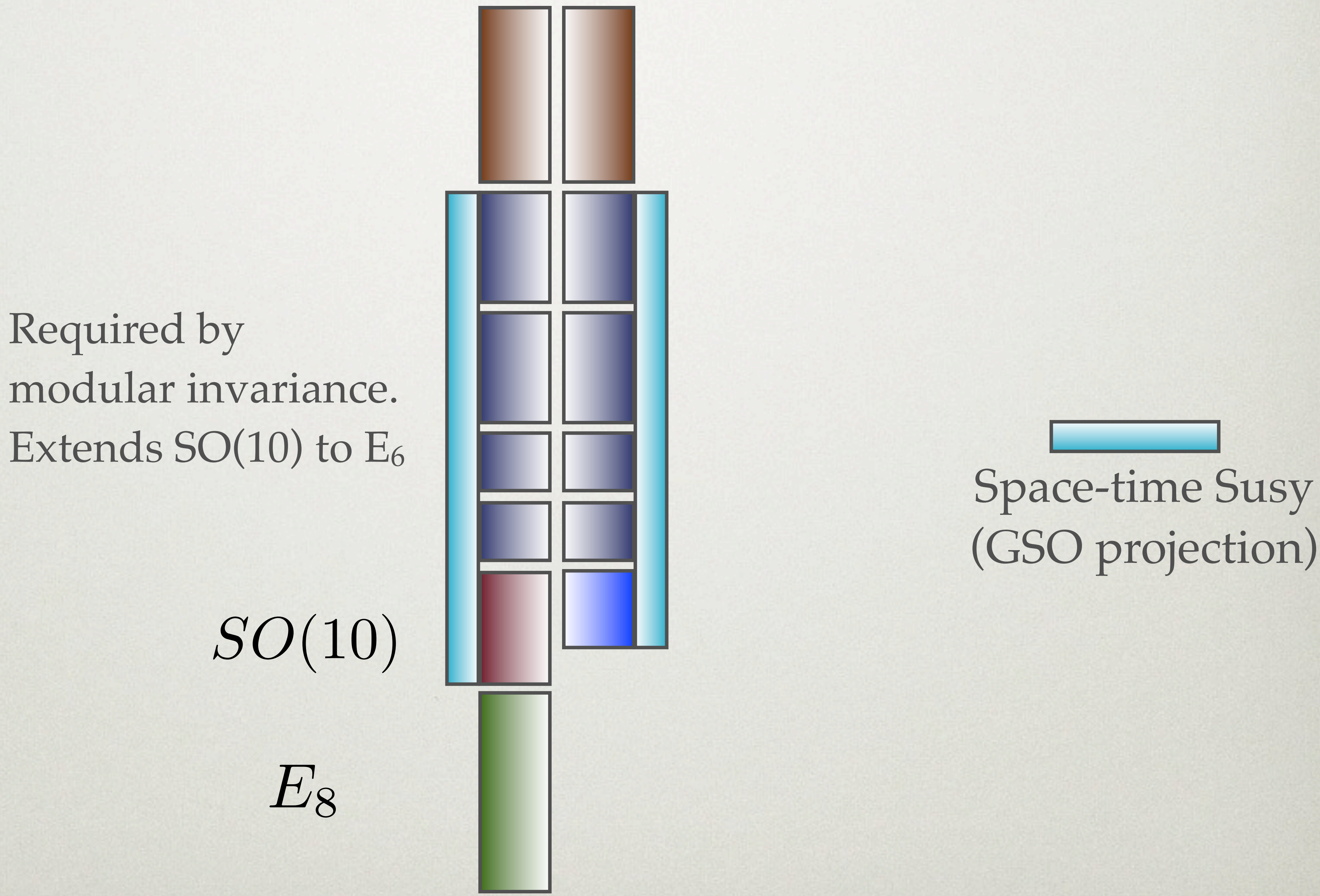
E_8





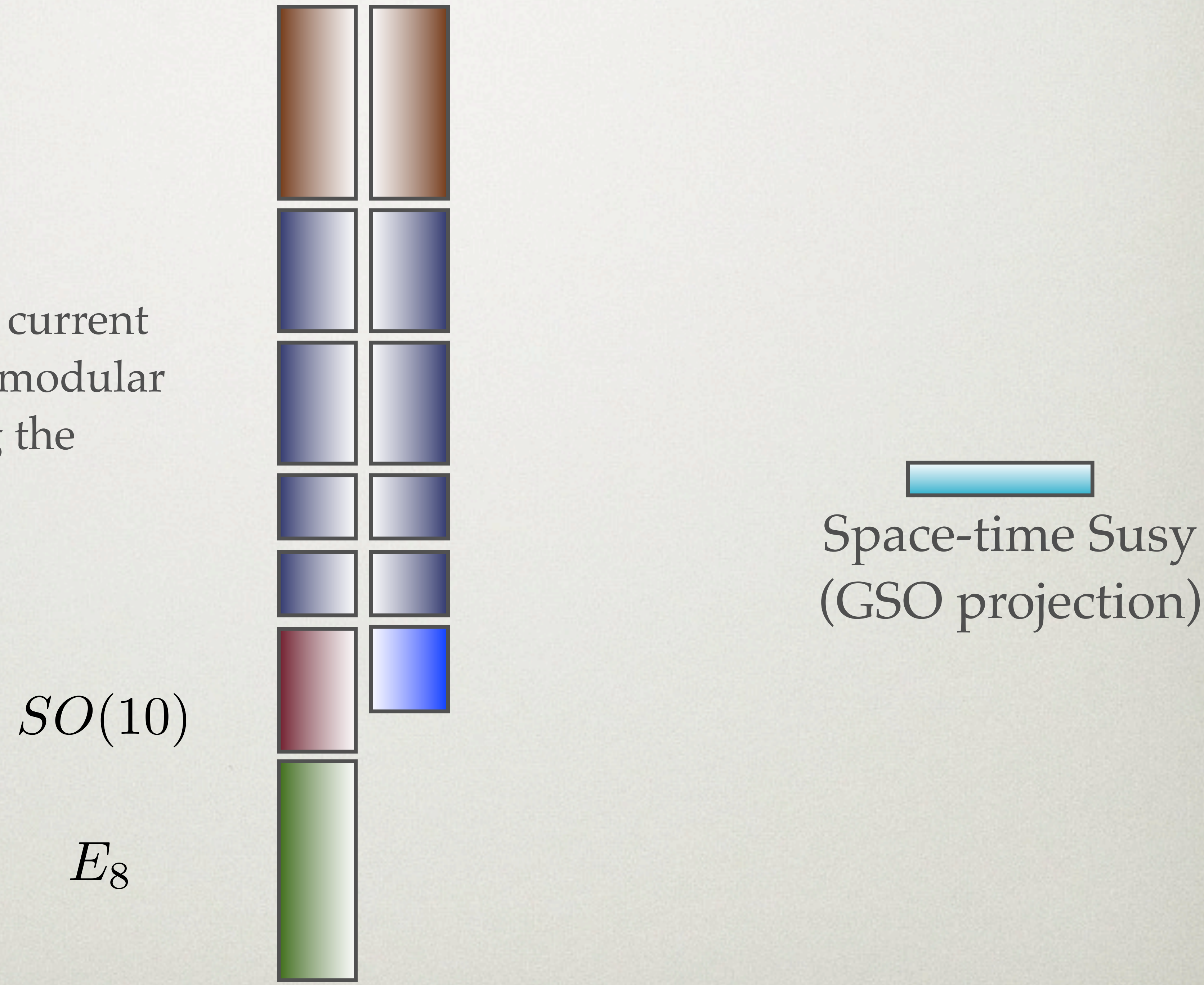
Space-time Susy
(GSO projection)

Imposing space-time supersymmetry



But there exist other solutions to modular invariance

Extension by an isomorphic current of higher weight. Preserves modular invariance without affecting the massless spectrum



Schellekens, Yankielowicz (1989)

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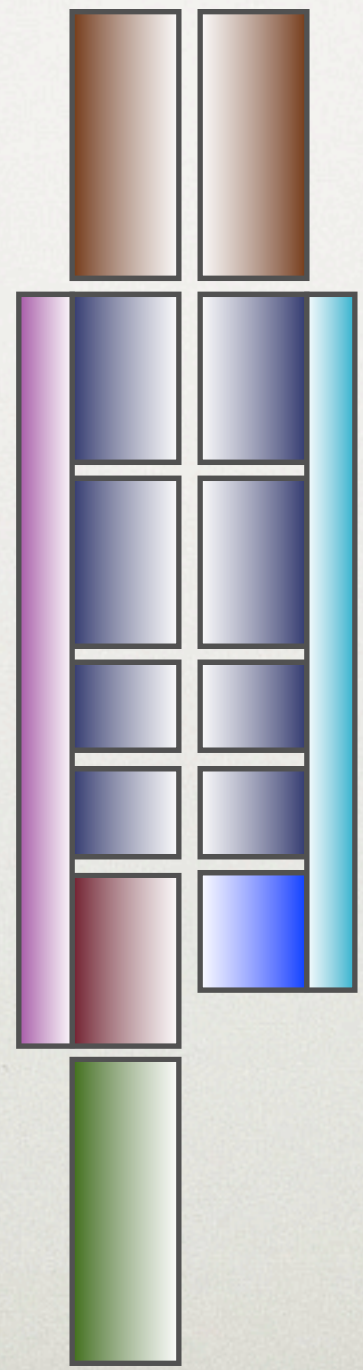

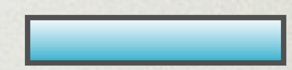

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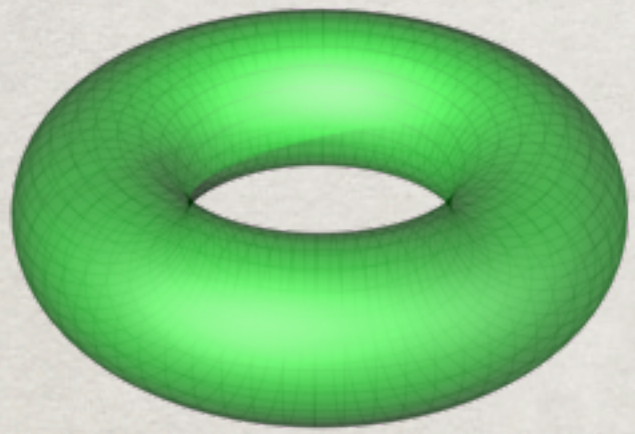
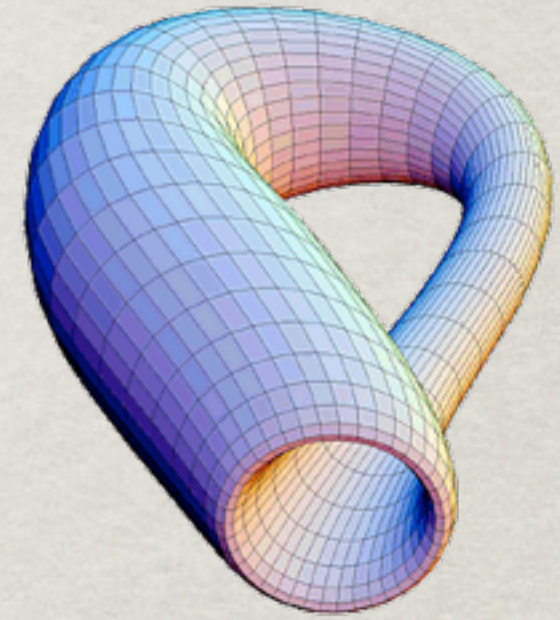
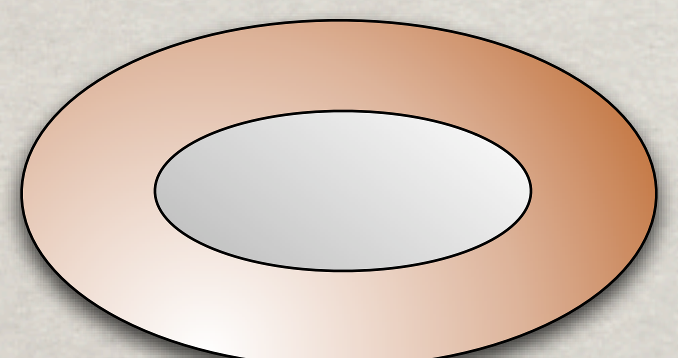
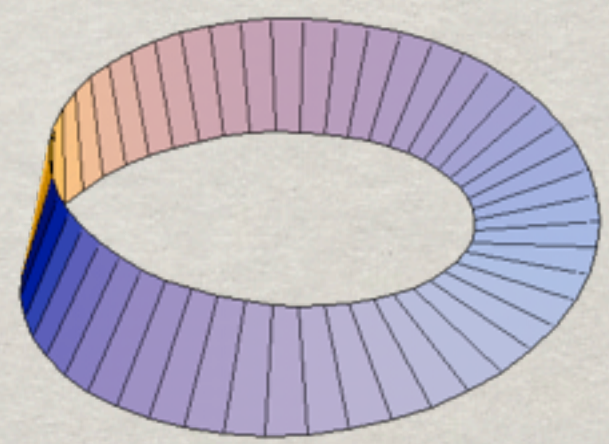
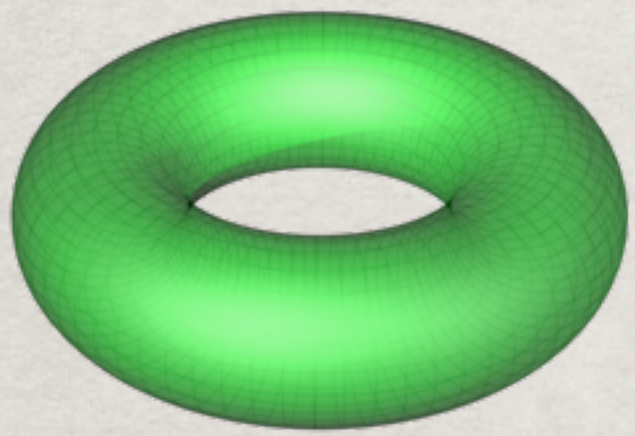
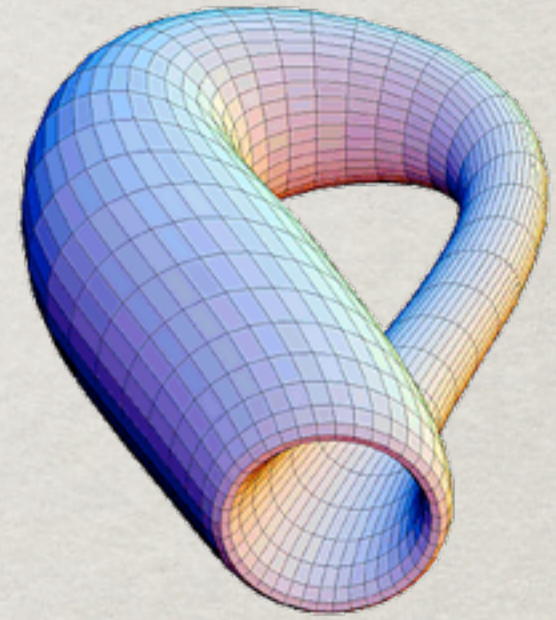
Open Strings

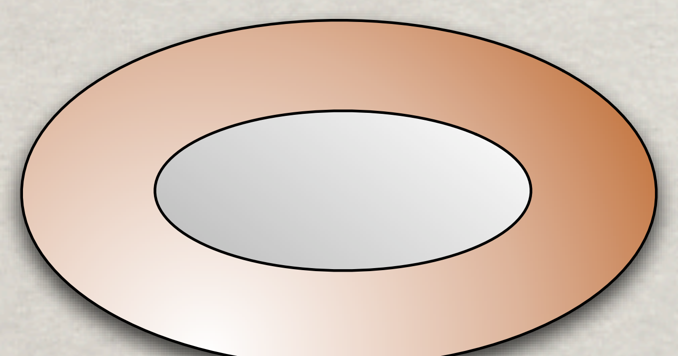
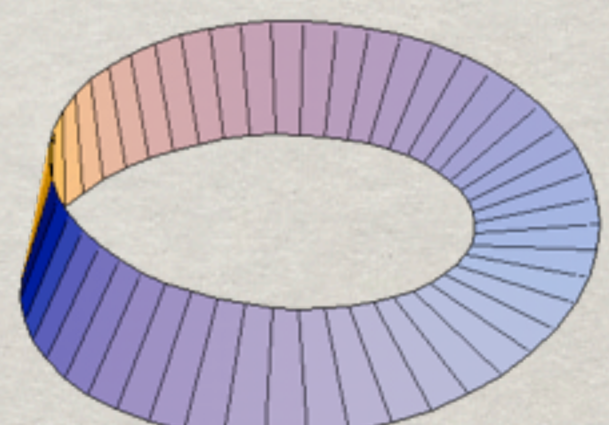
Orientifold Partition Functions

$\frac{1}{2}\Bigg\{$  $+$  $\Bigg\}$

$\frac{1}{2}\Bigg\{$  $+$  $\Bigg\}$

Orientifold Partition Functions

$\frac{1}{2}\Big\{$  +  $\Big\}$

$\frac{1}{2}\Big\{$  +  $\Big\}$

Orientifold Partition Functions

- Closed $$\frac{1}{2}\left[\sum_{ij}\chi_i(\tau)Z_{ij}\chi_i(\bar{\tau})+\sum_i K_i\chi_i(2\tau)\right]$$

- Open $$\frac{1}{2}\left[\sum_{i,a,n}N_aN_b{A^i}_{ab}\chi_i(\frac{\tau}{2})+\sum_{i,a}N_a{M^i}_a\hat{\chi}_i(\frac{\tau}{2}+\frac{1}{2})\right]$$

$i:$ Primary field label (finite range)

$a:$ Boundary label (finite range)

$\chi_i:$ Character

$N_a:$ Chan-Paton (CP) Multiplicity

The ends of open strings give rise to U(N), O(N) or Sp(2N) gauge groups.

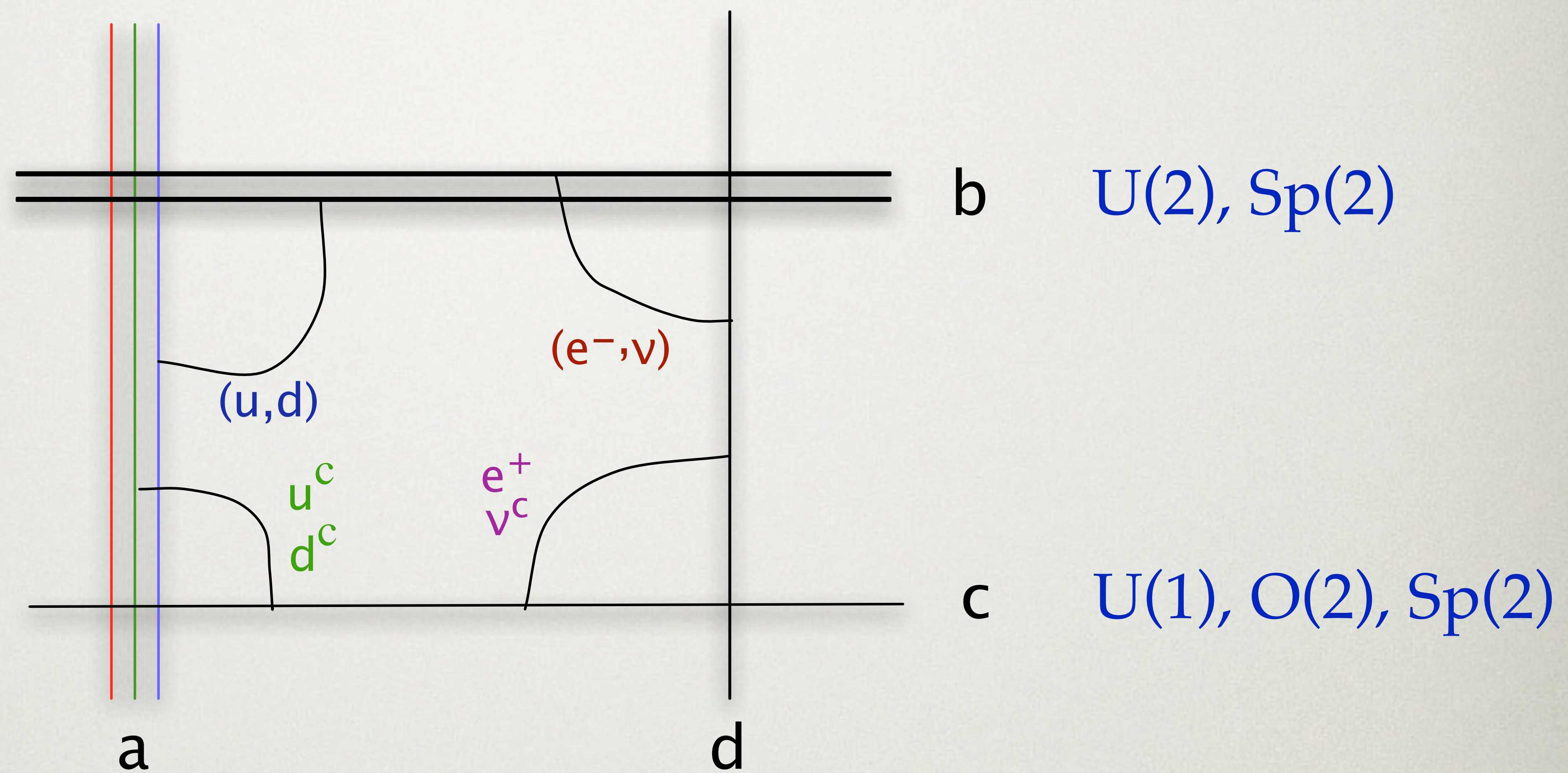
Since each open string has two ends, matter must be in bi-fundamentals (or rank-two tensors).

One may think of the endpoints as open strings ending on a membrane or a stack of N membranes. Traditional (pre-1995) open strings had Neumann boundary conditions and end on a space-time filling membrane. This is merely a change of language.

By allowing Dirichlet boundary conditions one can consider membranes that live only in a subset of all available dimensions, for example D=4 + some of the internal dimensions. They may intersect each other in the internal dimensions. Intersections give rise to massless matter.

By considering suitable combinations of stacks of branes one may obtain the standard model.

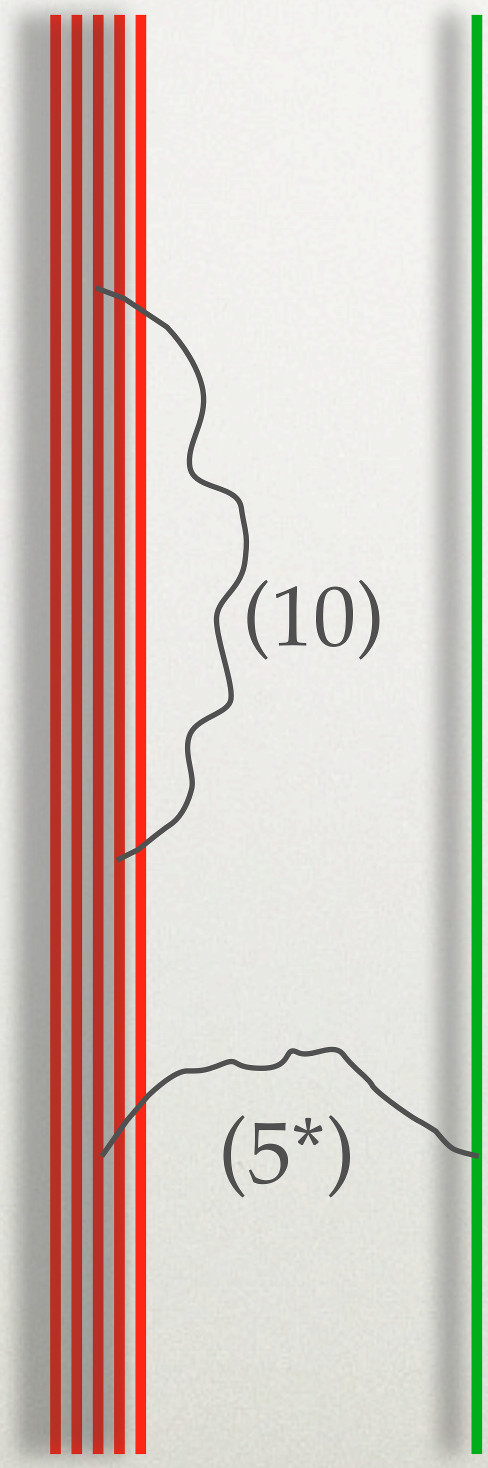
The Madrid Model*



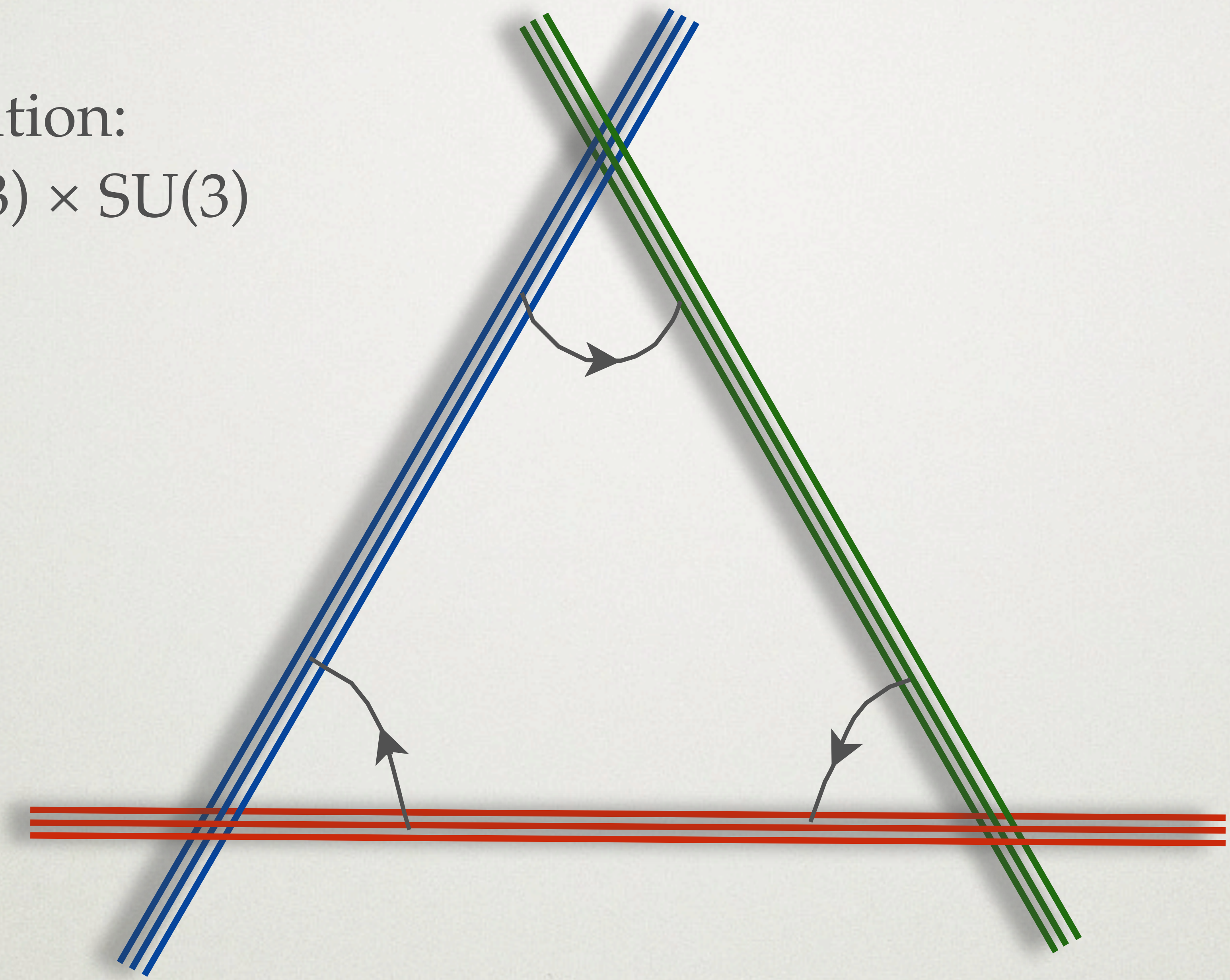
$$Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Qd$$

(*) Ibanez, Marchesano, Rabadan (2000)

SU(5)



Trinification:
$SU(3) \times SU(3) \times SU(3)$



$$(3, 3^*, 1) + (3^*, 1, 3) + (1, 3, 3^*)$$

The different models are distinguished by the realization of the Standard Model generator Y

$$Y = (x - \tfrac{1}{3})Q_{\mathbf{a}} + (x - \tfrac{1}{2})Q_{\mathbf{b}} + xQ_{\mathbf{c}} + (x-1)Q_{\mathbf{d}}$$

The following three possibilities exist*

1. $x=½$ (Madrid model, Pati-Salam model, ...)
2. $x=0$ (SU(5), ...)
3. x not quantized. Then the configuration is orientable (trinification)

(*)Anastasopoulos, Dijkstra, Kiritsis, Schellekens (2006)

Explicit realizations

It's easy enough to draw these pictures.
But finding an explicit example is another matter.
This involves:

- Finding a suitable CFT.
- Finding a type-IIB modular invariant partition function.
- Computing the "boundary coefficients" and the "crosscap coefficients"(*)
- Computing the Annulus, Klein bottle and Moebius coefficients.
- Checking if the massless spectrum matches the Standard Model.
- Checking if Y remains massless
- Cancelling the disk and crosscap tadpoles

(*) Cardy (1989), Sagnotti, Pradisi, Stanev, Bianchi (1990-1996), Fuchs, Schweigert, Huiszoon, Sousa, Walcher (1995-2000), ...

The long road to the SM

- Angelantonj, Bianchi, Pradisi, Sagnotti, Stanev (1996)
  Chiral spectra from Orbifold-Orientifolds

- Aldazabal, Franco, Ibanez, Rabadan, Uranga (2000)
  Blumenhagen,Görlich,Körs,Lüst (2000)
  Ibanez, Marchesano, Rabadan (2001)
  Non-supersymmetric SM-Spectra with RR tadpole cancellation

- Cvetic, Shiu, Uranga (2001)
  Supersymmetric SM-Spectra with chiral exotics

- Blumenhagen, Görlich, Ott (2002)
  Honecker (2003)
  Supersymmetric Pati-Salam Spectra with brane recombination

- Dijkstra, Huiszoon, Schellekens (2004)
  Supersymmetric Standard Model (Gepner Orientifolds)

- Honecker, Ott (2004)
  Supersymmetric Standard Model (Z_6 orbifold/orientifold)

Gauge group: Exactly SU(3) × SU(2) × U(1)!

[U(3)×Sp(2)×U(1)×U(1), Massive B-L, No hidden sector]

3 x	(V	,V	,0	,0)	chirality	3	Q
3 x	(V	,0	,V	,0)	chirality	-3	U*
3 x	(V	,0	,V*	,0)	chirality	-3	D*
3 x	(0	,V	,0	,V)	chirality	3	L
5 x	(0	,0	,V	,V)	chirality	-3	E*+(E+E*)
3 x	(0	,0	,V	,V*)	chirality	3	N*
18 x	(0	,V	,V	,0)			Higgs
2 x	(V	,0	,0	,V)			
2 x	(Ad	,0	,0	,0)			
2 x	(A	,0	,0	,0)			
6 x	(S	,0	,0	,0)			
14 x	(0	,A	,0	,0)			
6 x	(0	,S	,0	,0)			
9 x	(0	,0	,Ad	,0)			
6 x	(0	,0	,A	,0)			
14 x	(0	,0	,S	,0)			
3 x	(0	,0	,0	,Ad)			
4 x	(0	,0	,0	,A)			
6 x	(0	,0	,0	,S)			

Dijkstra, Huiszoon, Schellekens (2004)

Gauge group: Exactly SU(3) × SU(2) × U(1)!

[U(3)×Sp(2)×U(1)×U(1), Massive B-L, No hidden sector]

3	x (V	,V	,0	,0)	chirality	3	Q
3	x (V	,0	,V	,0)	chirality	-3	U*
3	x (V	,0	,V*	,0)	chirality	-3	D*
3	x (0	,V	,0	,V)	chirality	3	L
$\boxed{5}$	x (0	,0	,V	,V)	chirality	-3	E*+(E+E*)
3	x (0	,0	,V	,V*)	chirality	3	N*
18	x (0	,V	,V	,0)			Higgs
2	x (V	,0	,0	,V)			
2	x (Ad	,0	,0	,0)			
2	x (A	,0	,0	,0)			
6	x (S	,0	,0	,0)			
14	x (0	,A	,0	,0)			
6	x (0	,S	,0	,0)			
9	x (0	,0	,Ad	,0)			
6	x (0	,0	,A	,0)			
14	x (0	,0	,S	,0)			
3	x (0	,0	,0	,Ad)			
4	x (0	,0	,0	,A)			
6	x (0	,0	,0	,S)			

Vector-like matter

V=vector

A=Anti-symm. tensor

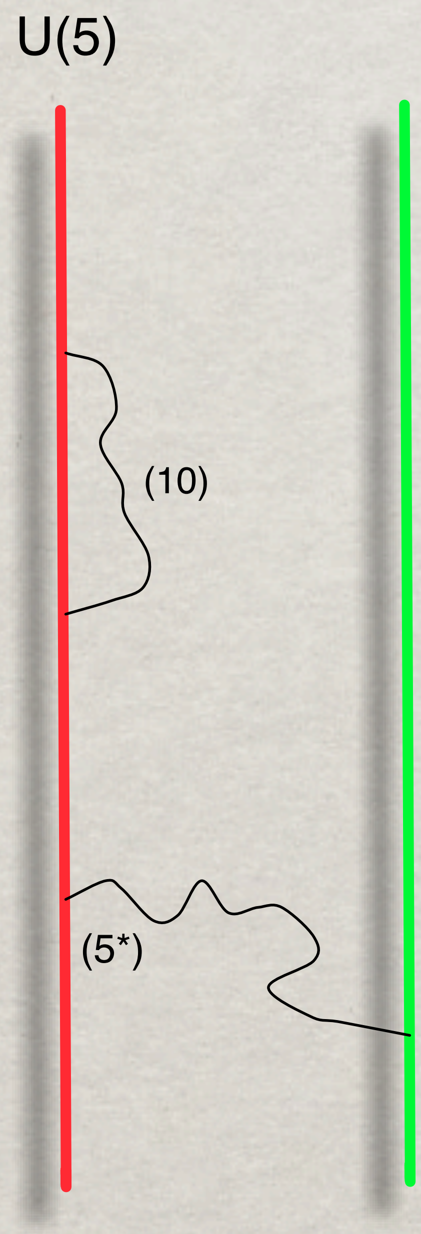
S=Symmetric tensor

Ad=Adjoint

Dijkstra, Huiszoon, Schellekens (2004)

An SU(5) model

Gauge group is just SU(5)!



U5 O1 O1

3 x	(A	,0	,0	)	chirality 3
11 x	(V	,V	,0	)	chirality -3
8 x	(S	,0	,0	)	
3 x	(Ad	,0	,0	)	
1 x	(0	,A	,0	)	
3 x	(0	,V	,V	)	
8 x	(V	,0	,V	)	
2 x	(0	,S	,0	)	
4 x	(0	,0	,S	)	
4 x	(0	,0	,A	)	

(*)Anastasopoulos, Dijkstra, Kiritsis, Schellekens (2006)

Challenges

Generically:

- Stabilizing moduli
- Breaking supersymmetry
- Getting the right parameter values (fermion masses, couplings)

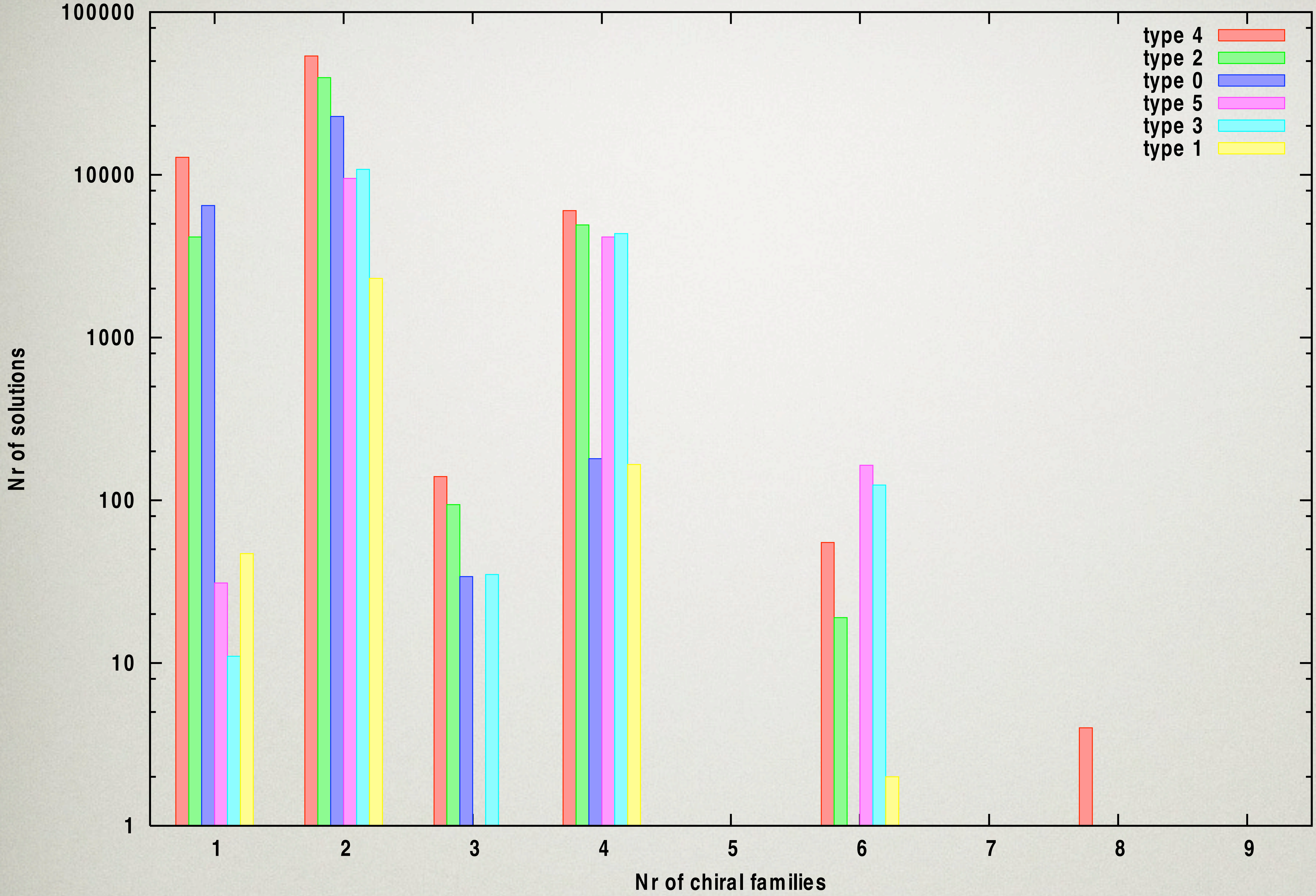
Challenges

Here I will focus on two issues

- The number of families
- GUTs versus charge quantization

In both cases we can get the right answer (see the examples), but does it really come out naturally?

In neither case there is a clear "anthropic" explanation available.



Dijkstra, Huiszoon, Schellekens (2004)
See also Gmeiner et. al. "One in a billion"

Electric Charge Quantization

- All color singlets in the Standard Model have integer charges.
- This can be most easily understood by assuming an embedding in SU(5) (or SO(10)).
- But how does this work in string theory?

Electric Charge Quantization

- The heterotic string provides SO(10) naturally.
  But a theorem I proved in 1989 shows that once SO(10) is broken to SU(3) × SU(2) × U(1) the spectrum *must* contain fractional electric charges (though they may be massive).
- In the Madrid configuration each string endpoint contributes ½ to the unconfined electric charge.
  So this is OK as long as there are no extra ("hidden") branes.
  On the other hand, the three gauge couplings are completely unrelated.
- In the SU(5)-type brane models the couplings unify and charge quantization is automatic. But in the entire scan such models occur rarely. So string theory then provides no compelling reasons for unification.

A return to the heterotic string

I. SO(10) breaking

CERN–TH.5440/89

NEW MODULAR INVARIANTS FOR N=2 TENSOR PRODUCTS AND FOUR-DIMENSIONAL STRINGS

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and

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ABSTRACT

The construction of modular invariant partition functions of tensor products of $N = 2$ superconformal field theories is clarified and extended by means of a recently proposed method using simple currents, *i.e.* primary fields with simple fusion rules. Apart from providing a conceptually much simpler way of understanding space-time and world-sheet supersymmetry projections in modular invariant string theories, this makes a large class of modular invariant partition functions accessible for investigation. We demonstrate this by constructing thousands of (2,2), (1,2) and (0,2) string theories in four dimensions, including more than 40 new three generation models.

6. Outlook and conclusions

Clearly the method we have advocated in this paper greatly extends the list of four-dimensional string theories accessible to exploration. However, this is by no means all one can do. Up to now we have always kept an unbroken $SO(10) \times E_8$ Kac-Moody algebra on the left. However, just as one can break the left-moving "space-time" and world-sheet supersymmetries, one can break this KM-algebra as well. To do so, one simply starts with characters of some conformal sub-algebra of $SO(10) \times E_8$. Of course one wants to get the full $SO(10) \times E_8$ algebra on the *right*, in order to be able to map this sector to a fermionic one. But this can always be achieved by putting some projection matrices in front of the right-moving characters to add the missing $SO(10) \times E_8$ roots.

This opens the way to constructing string theories whose gauge group is something a bit closer to the standard model than $SO(10)$, perhaps even $SU(3) \times SU(2) \times U(1)^n$ (where n is almost inevitably larger than 1). There is no reason why one could not get 3 generations in such a model, and in fact there could well be many more models than those listed in table III, since the center of the conformal field theory one starts with is even larger. We hope to come back to this in the future.

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The future has finally arrived (Gato-Rivera, Schellekens, 2010)

RCFT:
Heterotic vs Orientifold

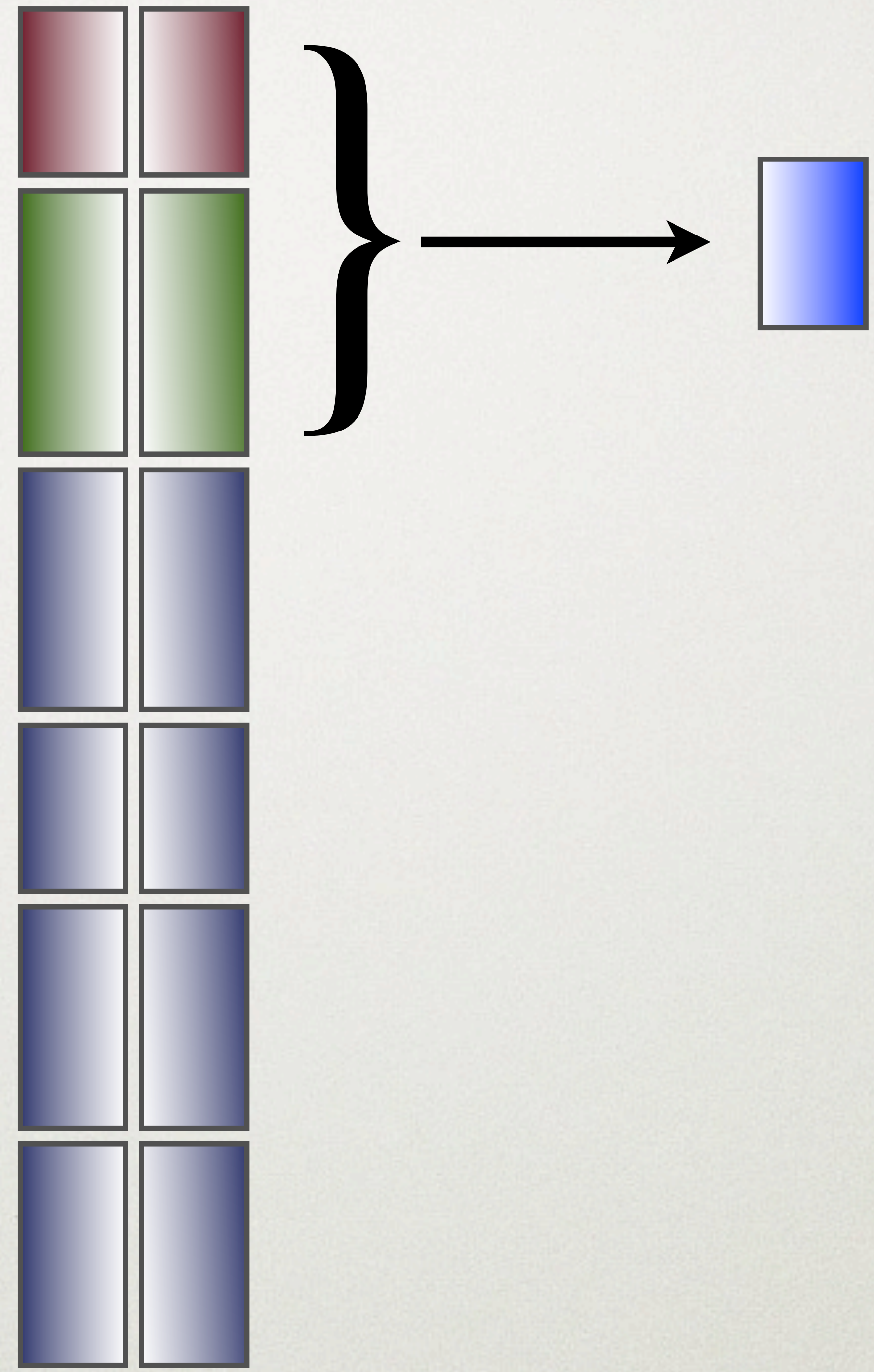
During the last five years, orientifolds were scanned systematically for Standard Model spectra

Dijkstra, Huiszoon, Schellekens
Gmeiner, Blumenhagen, Honecker, Lust, T. Weigand
Anastasopoulos, Dijkstra, Kiritsis, Schellekens
Douglas, Taylor
Kiritsis, Lennek, Schellekens
Gmeiner, Honecker

Few comparable results exist for heterotic strings. All we have are Hodge number scans[1], and fermionic construction scans[2]

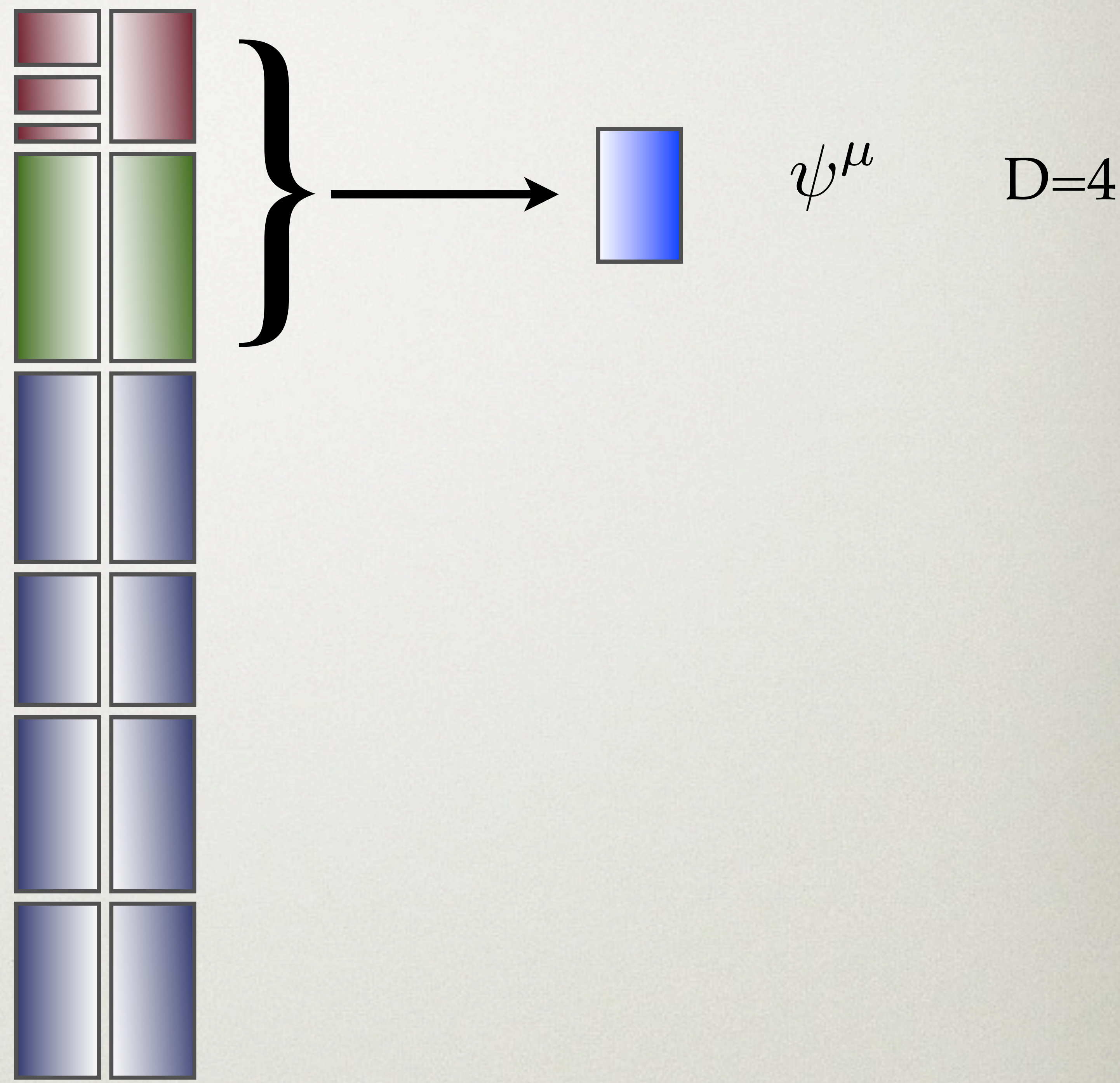
(1) *Lutken, Ross (1988)*
Schellekens, Yankielowicz (1989)
Fuchs, Klemm, Scheich, Schmidt (1989)
Kreuzer, Skarke (1992)
Donagi, Faraggi (2004),
Ploger, Ramos-Sanchez, Ratz, Vaudrevange (2007)
Donagi, Wendland (2008)
Kiritsis, Lennek, Schellekens (2008)

(2) *Dienes, Senechal (2007)*
Assel, Christodoulides, Faraggi, Kounnas, Rizos (2009)



ψ^μ D=4

SO(10) currents replaced by operators of higher weight



Gauge group $H \subset SO(10)$ $(\times H' \subset E_8 \times ....)$

Breaking SO(10)

Consider* $SU(3) \times SU(2) \times U(1)_{30} \times U(1)_{20} \subset SO(10)$

This should give chiral families of $SU(3) \times SU(2) \times U(1)$ with standard gauge coupling unification.

Indeed, it does, but there was a major disappointment:
All these spectra contain fractionally charged particles.

This was easily seen to be a very general result.
(A.N. Schellekens, Phys. Lett. B237, 363, 1990).

But there are ways out: they can be massive, vector-like (or confined by another gauge group)

(*) A.N. Schellekens and S. Yankielowicz (1989)
Other subgroups were considered by Blumenhagen, Wisskirchen, Schimmrigk (1995, 1996)

SO(10) sub-algebras

Nr.	Name	Current	Order	Gauge group	Grp.	CFT
0	SM, Q=1/6	$(1,1,0,0)$	1	$SU(3)\times SU(2)\times U(1)\times U(1)$	$\frac{1}{6}$	$\frac{1}{6}$
1	SM, Q=1/3	$(1,2,15,0)$	2	$SU(3)\times SU(2)\times U(1)\times U(1)$	$\frac{1}{6}$	$\frac{1}{3}$
2	SM, Q=1/2	$(3,1,10,0)$	3	$SU(3)\times SU(2)\times U(1)\times U(1)$	$\frac{1}{6}$	$\frac{1}{2}$
3	LR, Q=1/6	$(1,1,6,4)$	5	$SU(3)\times SU(2)_L\times SU(2)_R\times U(1)$	$\frac{1}{6}$	$\frac{1}{6}$
4	SU(5) GUT	$(\bar{3},2,5,0)$	6	$SU(5)\times U(1)$	1	1
5	LR, Q=1/3	$(1,2,3,-8)$	10	$SU(3)\times SU(2)_L\times SU(2)_R\times U(1)$	$\frac{1}{6}$	$\frac{1}{3}$
6	Pati-Salam	$(\bar{3},0,2,8)$	15	$SU(4)\times SU(2)_L\times SU(2)_R$	$\frac{1}{2}$	$\frac{1}{2}$
7	SO(10) GUT	$(3,2,1,4)$	30	$SO(10)$	1	1

Results:

- Half-integer or third-integer charges can be avoided by clever choices of the CFT, but not simultaneously.
- In about half of the cases the fractional charges are present, but at least they are vector-like: they can get masses under perturbations

A return to the heterotic string

II The number of families

Schellekens, Yankielowicz (1989): *(2,2) , (1,2) unbroken SO(10)*

Gato-Rivera, Schellekens (2010): *(2,2) , (1,2), (0,2), broken SO(10)*

Number of families:

Turned out to be quantized in terms of a quantity Δ for each class of CFT's (there are 168+59 classes, each containing thousands of distinct spectra)

The following values of Δ occur for the 168 minimal model combinations and 58 of the 59 exceptional ones: 120, 96, 72, 60, 48, 40, 36, 32, 24, 12, 8, 6, 4 and 0.

There is one class with Δ=3, which indeed does contain 3-family models (Gepner, 1987)

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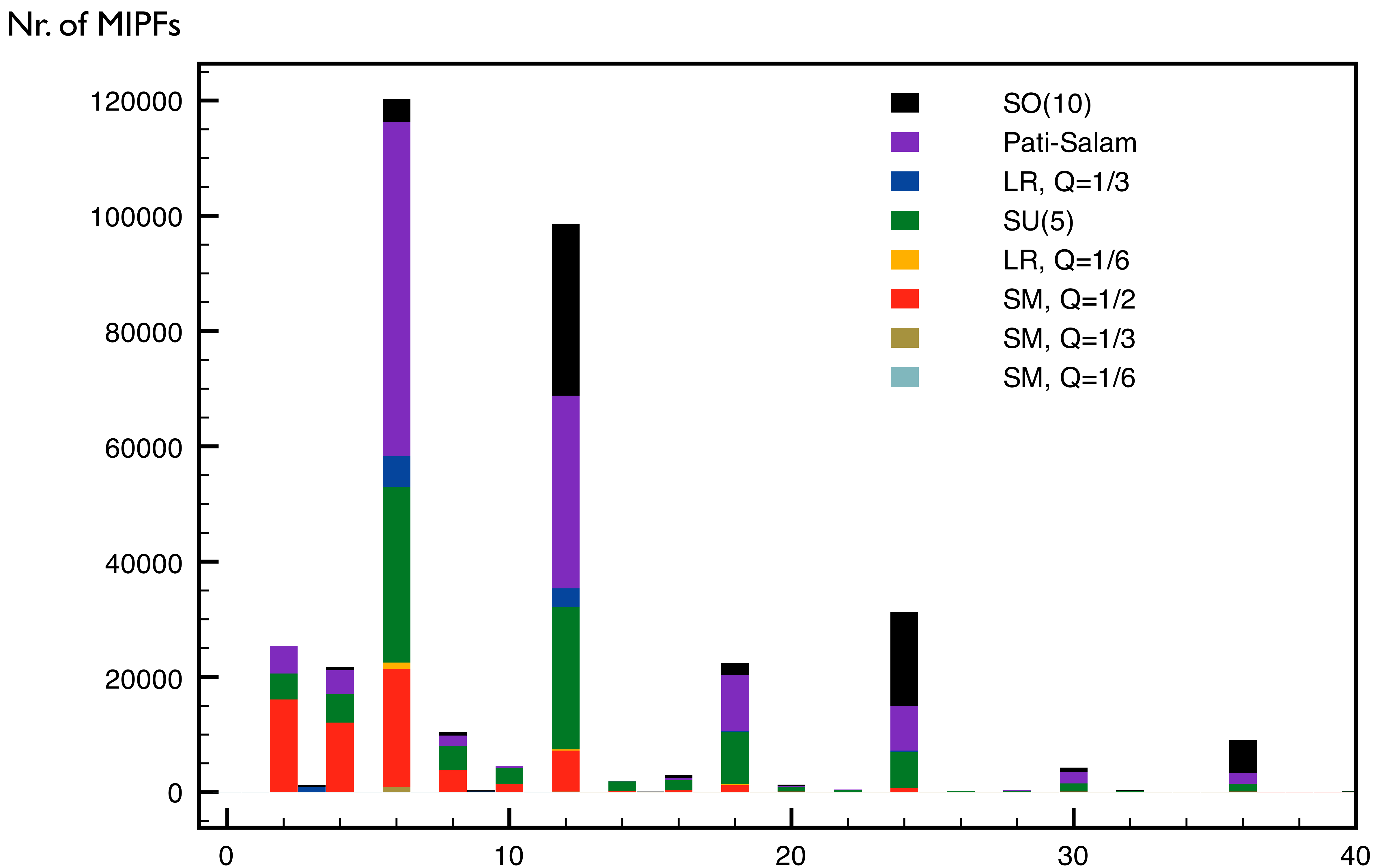
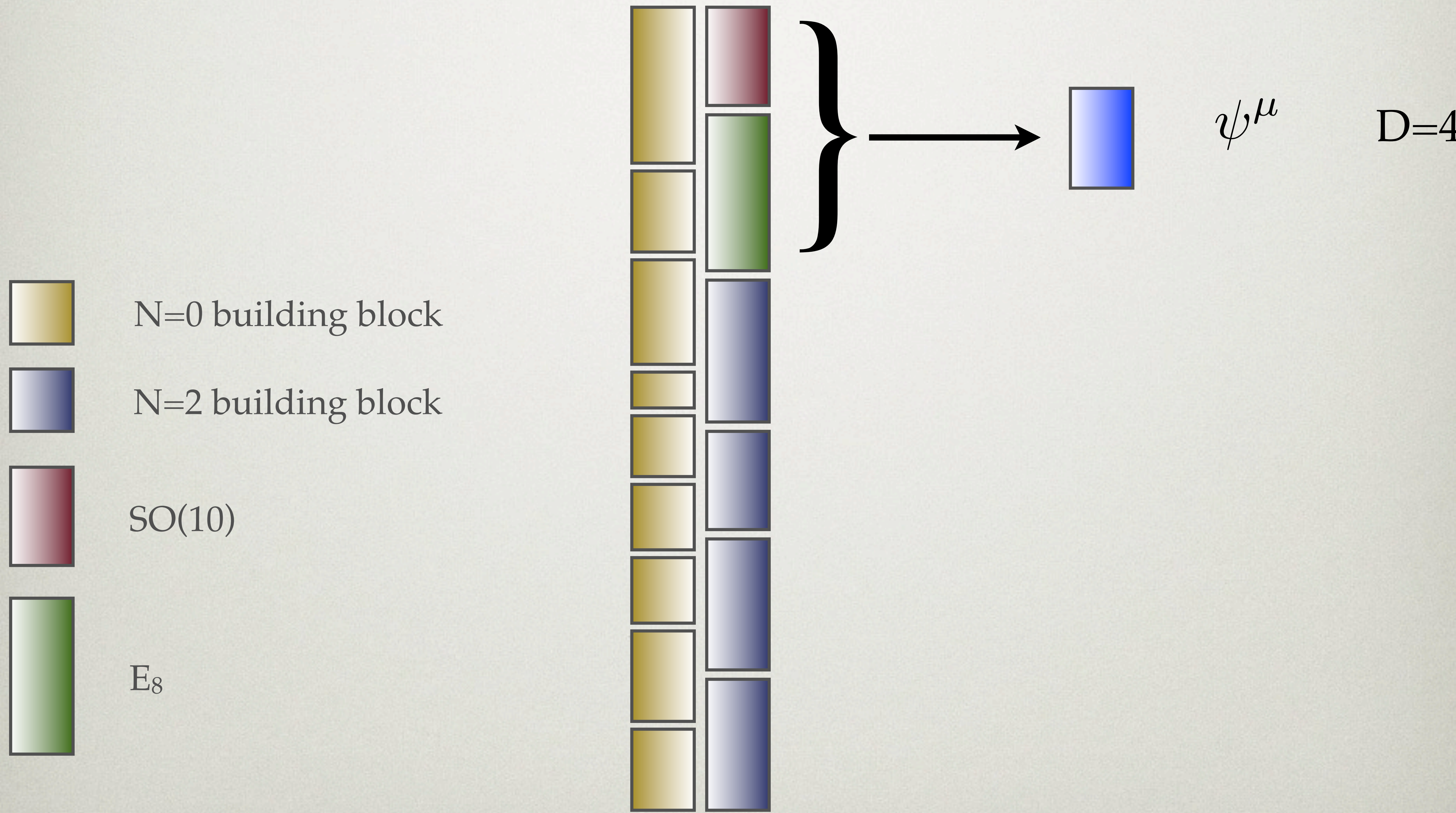
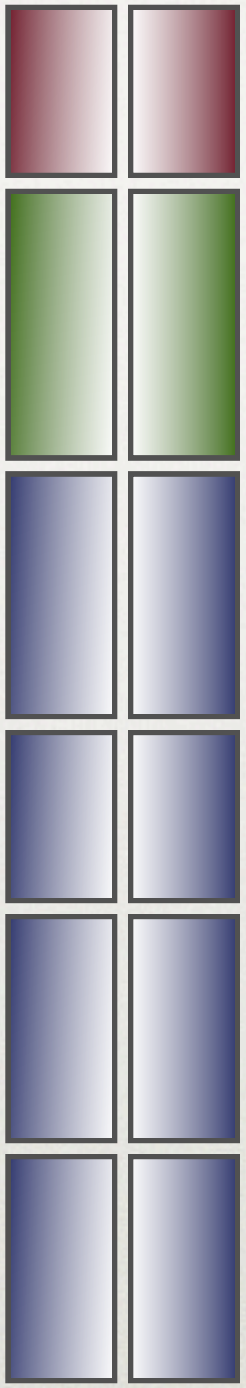
Family Distribution

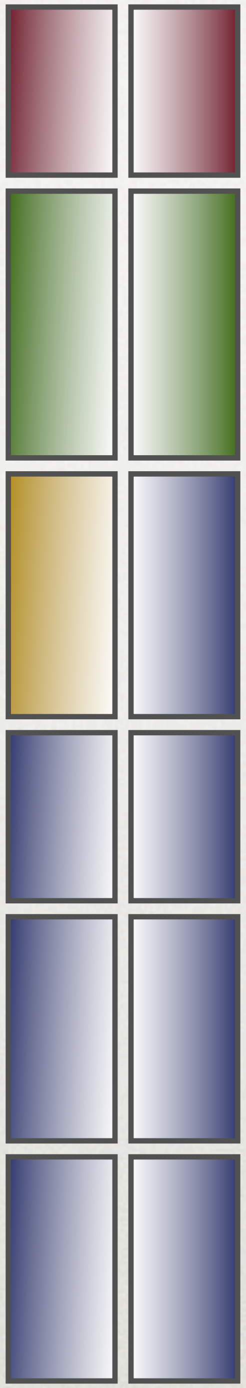


Heterotic weight lifting

General Heterotic String



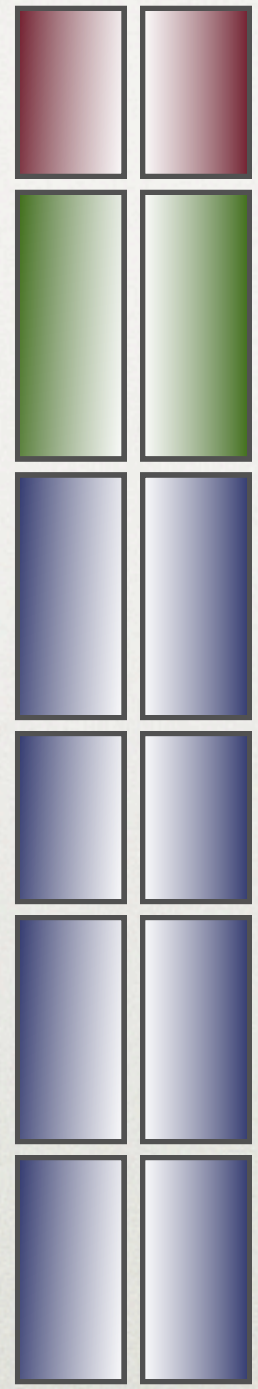




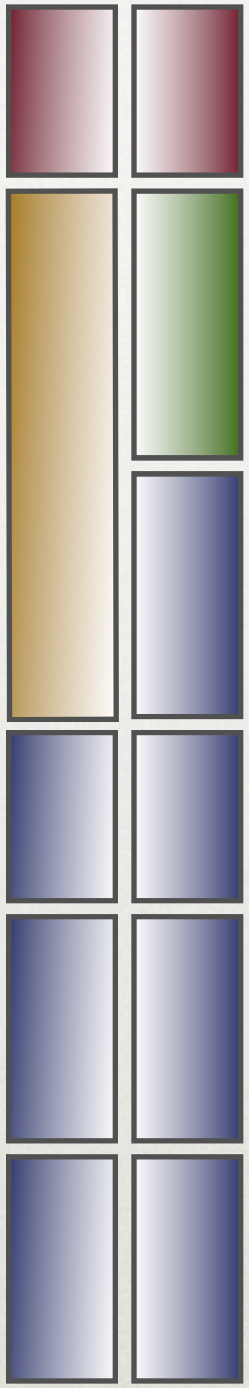
... but we have to find a N=0 CFT with the same S, T, and central charge as some N=2 model, without being identical to it.

This looks difficult.

But there is something else we could try:



Gato-Rivera, Schellekens, 2009



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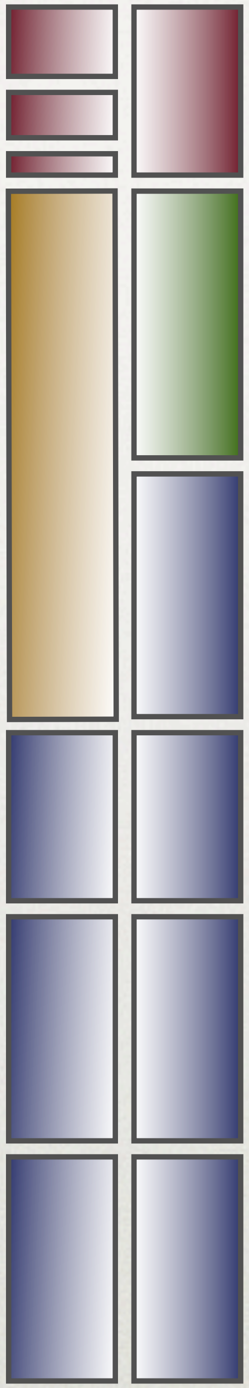
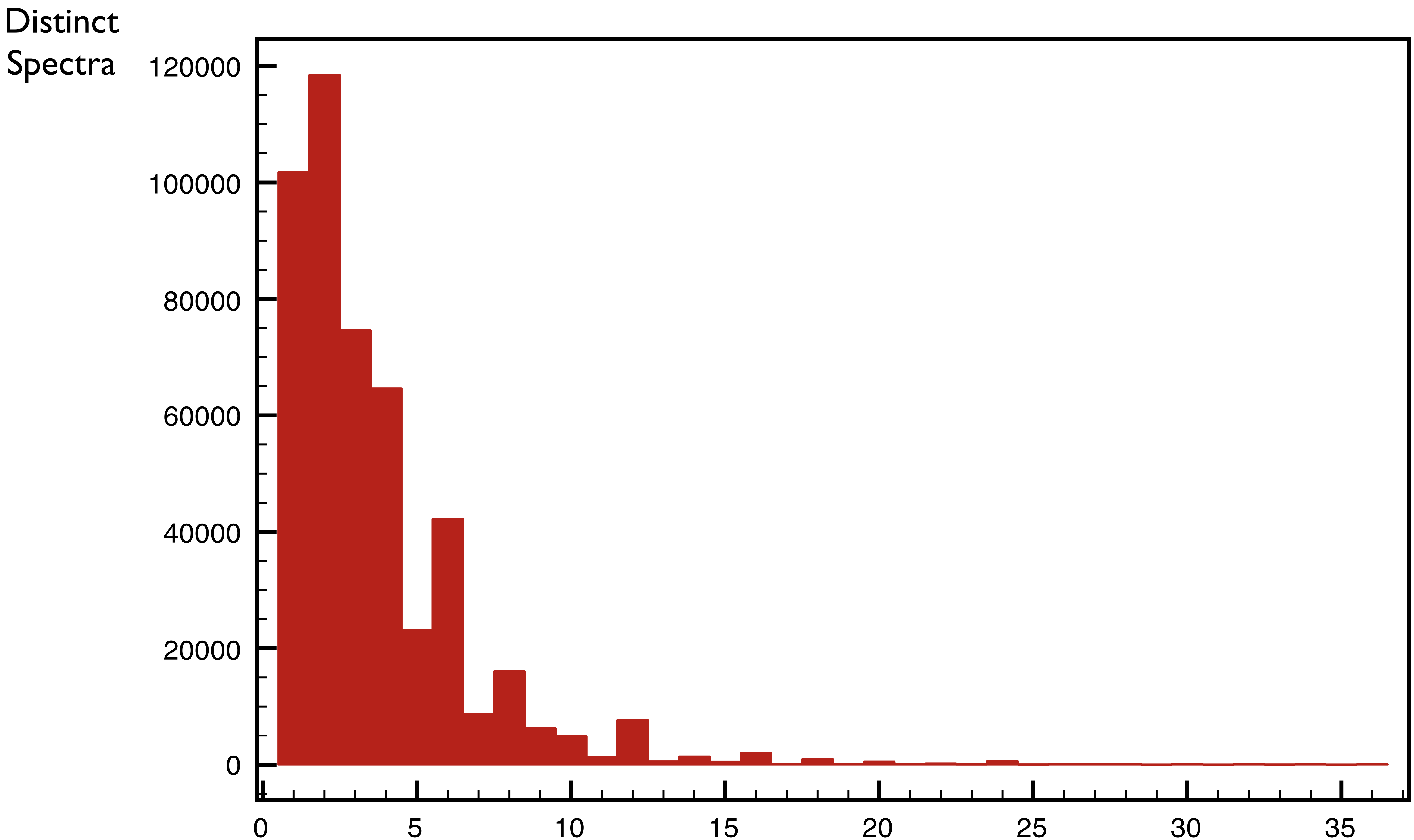


Gato-Rivera, Schellekens, 2009



Family distribution for 435 “lifted” Gepner models

Conclusions

- The rough features of the Standard Model come out very easily and in several ways in string theory.
- But there is a problem with GUTs: either they don't arise naturally, or they don't work as they should.
- The number of families is another worry.
- But on closer inspection, for heterotic strings both worries are reduced.