RCFT constructions of Heterotic Strings

Bert Schellekens

NIKHEF

Busan, StringVac11 *5 September 2011*

Some recent events

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J. Harvey, summary talk Strings 2011

Search for minimal dS solution without all the bells and whistles of KKLT. It is hard.

Landscape/multiverse skeptics may take some hope from these results, but it seems too early to know for sure.

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BBC

LHC results put supersymmetry theory 'on the spot'

Bitten the dust

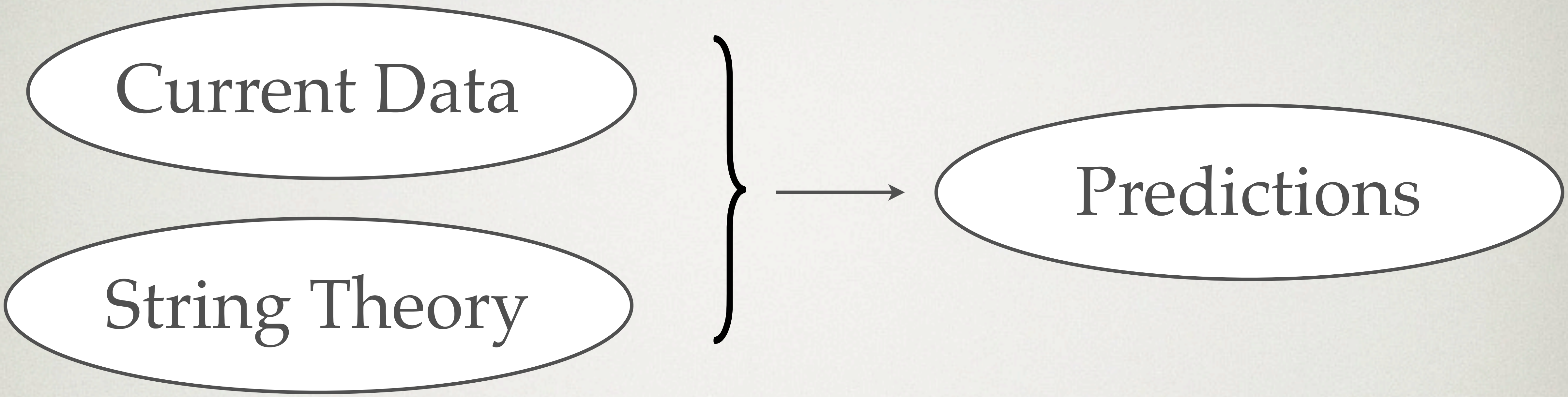
Disappointed

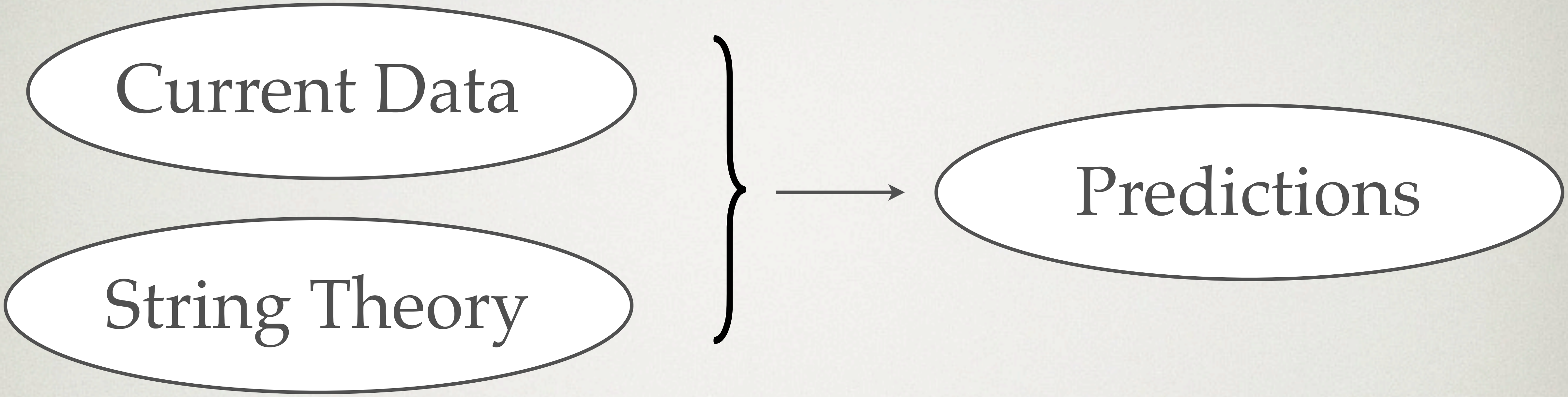
Down the drain

COMMENTS

- The Standard Model is perfectly OK without low energy supersymmetry.
- String theory does not predict low energy supersymmetry.
- Perhaps the “landscape” even predicts the opposite.
- The one Standard Model feature of String Theory that is most likely to survive (if anything survives) is the landscape.

But we should be able to learn a little bit more about the Standard Model than that it is merely an anthropically restricted but otherwise “random” point in a huge ensemble.


Current Data
String Theory
Predictions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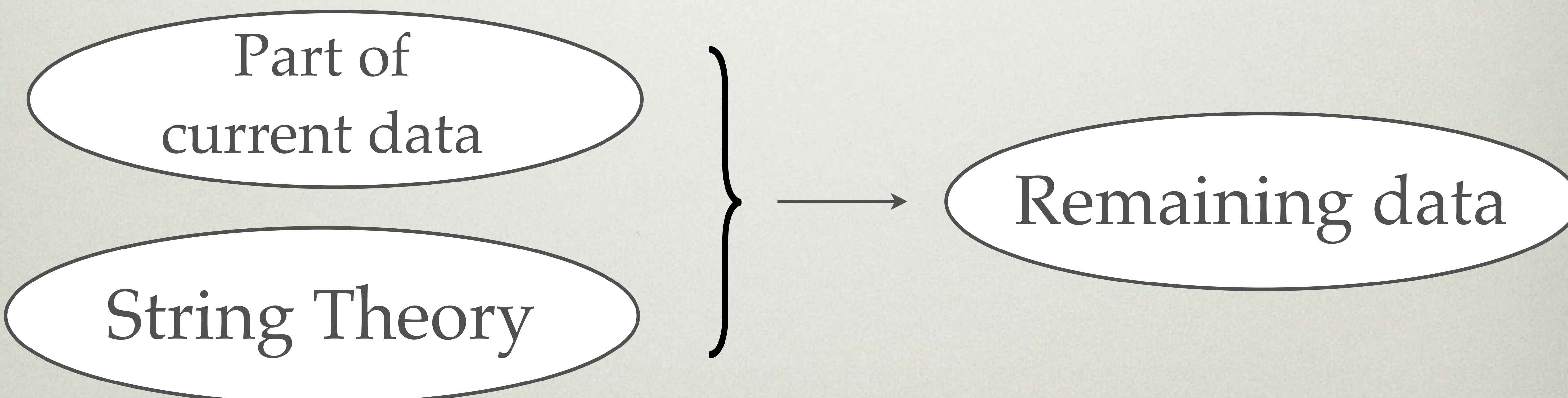

Part of
current data
String Theory
Remaining data

$$\left.\begin{array}{c}\text{Chirality, D=4}\\[1em]\text{String Theory}\end{array}\right\} \longrightarrow \text{SO(10)-like spectra}$$

Chirality, D=4

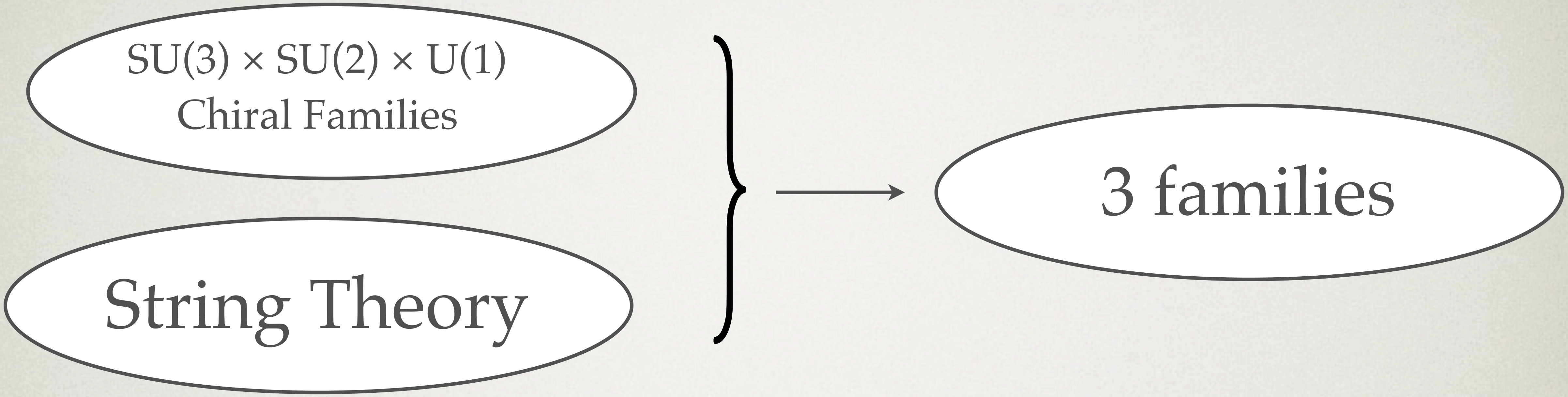
String Theory

$\longrightarrow$ SO(10)-like spectra

$SU(3) \times SU(2) \times U(1)$

String Theory

$\longrightarrow$ Family structure


SU(3) × SU(2) × U(1)
Chiral Families
String Theory
3 families

$SU(3) \times SU(2) \times U(1)$
Chiral Families

String Theory

3 families

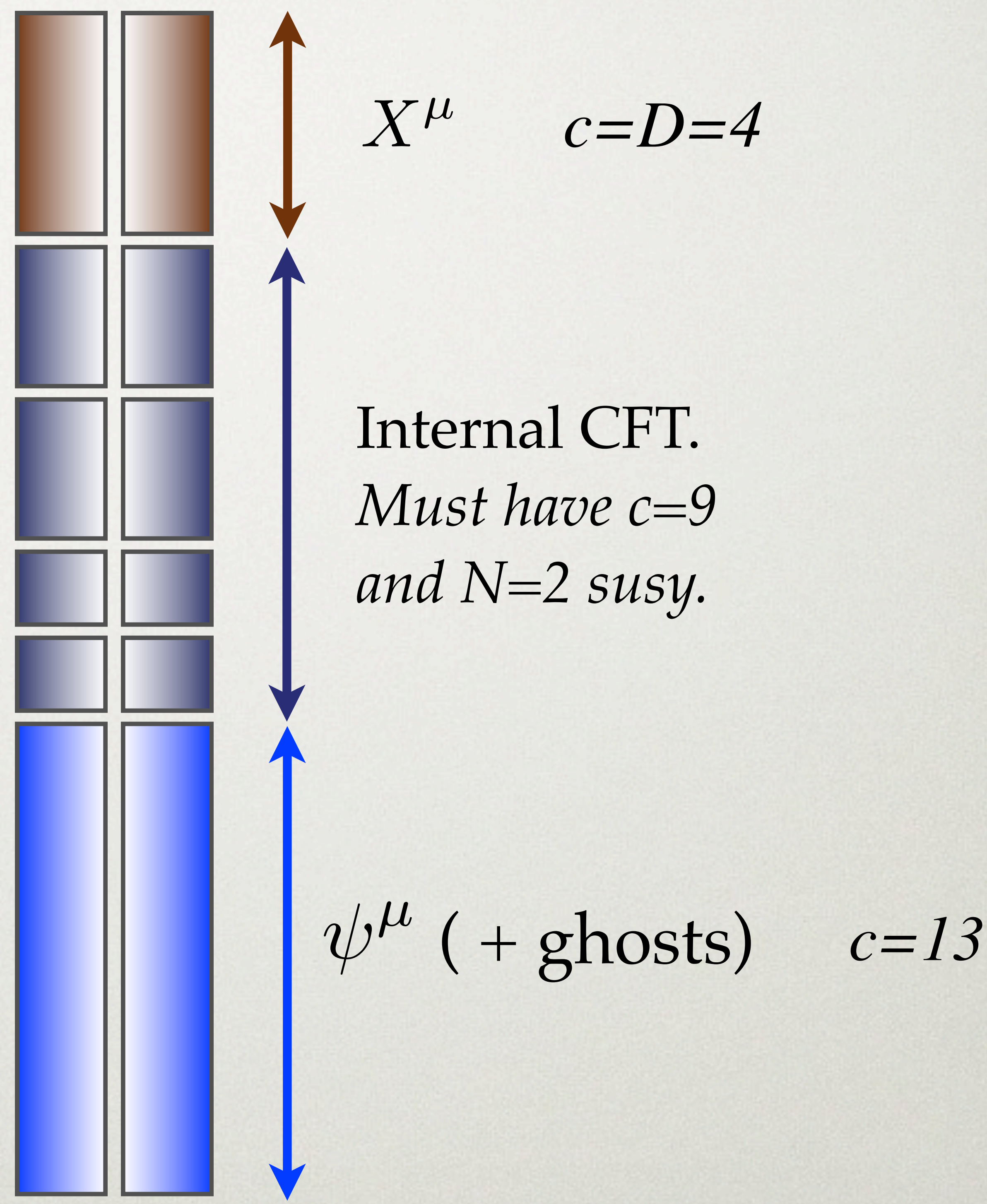
$SU(3) \times SU(2) \times U(1)$
Chiral Families

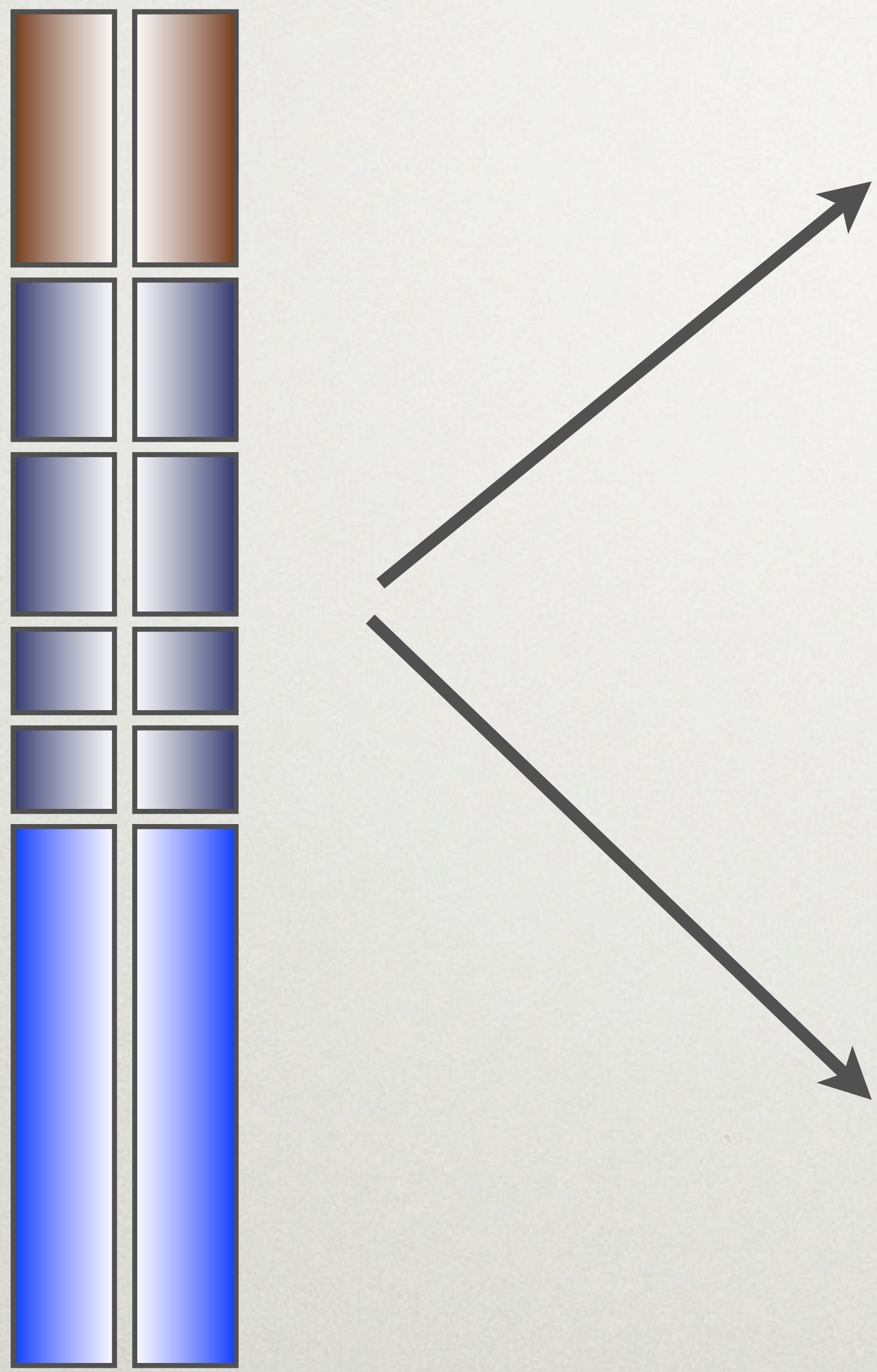
String Theory

No light fractional
charges

RCFT models: closed sector

Type-II strings





Heterotic

(Gepner,.....)

Orientifolds

(Sagnotti et. al, ...)

BUILDING BLOCK DATA

Required data

- The exact Virasoro spectrum

  $h_i, \; i = 1, \ldots, N_{primary}$

- The ground state dimensions.

- The modular matrix S_{ij}

  $S_{J0} = S_{00}$: J is a simple current

  Fusion: $[J].[i] = [Ji]$

  Used to build non-trivial MIPFs

- The fixed point resolution matrices S^J

  Act on fixed points of $J : [J].[f] = [f]$

The MIPFs

(Modular invariant Partition functions)

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

Each building block contributes factors to a discrete simple current group G

Example: $$\mathbb{Z}_2^3\times\mathbb{Z}_3\times\mathbb{Z}_{30}\times\mathbb{Z}_{20}^6$$

Now choose any(*) subgroup *H*, and a rational(*) matrix *X* satisfying $X+X^T=R$, where *R* is a given rational matrix (the "monodromy matrix").
Then for each(*) such matrix *X* we get a matrix $M_{ij}=M(H,X)$ defining a MIPF.

(Nucl.Phys. B411 (1994) 97-121, with Max Kreuzer)

This has a huge number of solutions; for $\mathbb{Z}_p^K$, p prime : *(with B. Gato-Rivera, 1992)*

$$N_{\mathrm{MIPF}}=\prod_{l=0}^{K-1}(1+p^l)$$

For p=5, K=7: $N_{\mathrm{MIPF}}=1.202.088.011.709.312$

(*) Restrictions apply.

Matrix S for chiral algebra extensions

(Fuchs, Schellekens, Schweigert (1996))

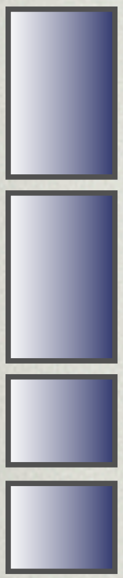
$$\tilde{S}_{(a,i),(b,j)} = \frac{|\mathcal{G}|}{\sqrt{|\mathcal{U}_a|\,|\mathcal{S}_a|\,|\mathcal{U}_b|\,|\mathcal{S}_b|}} \sum_{J\in\mathcal{G}} \Psi_i^a(J)\, S^J_{a,b}\, \Psi_j^b(J)^*$$

Boundary coefficients for non-trivial MIPFs

(Fuchs, Huiszoon, Schellekens, Schweigert, Walcher (2000))

$$B_{(i,J),[j,\psi]} = \sqrt{\frac{|\mathcal{G}|}{|\mathcal{S}_j|\,|\mathcal{C}_j|}}\, \frac{\alpha(J)\, S^J_{i,j}}{\sqrt{S_{0,i}}}\, \psi(J)^*$$

Building blocks we can use at present



- N=2 minimal models: Gepner models (168 combinations)

  Gepner (1987)
  Lutken, Ross (1988)
  Fuchs, Klemm, Scheich, Schmidt (1989)
  Schellekens, Yankielowicz (1989)
  Gato-Rivera, Schellekens (2010)

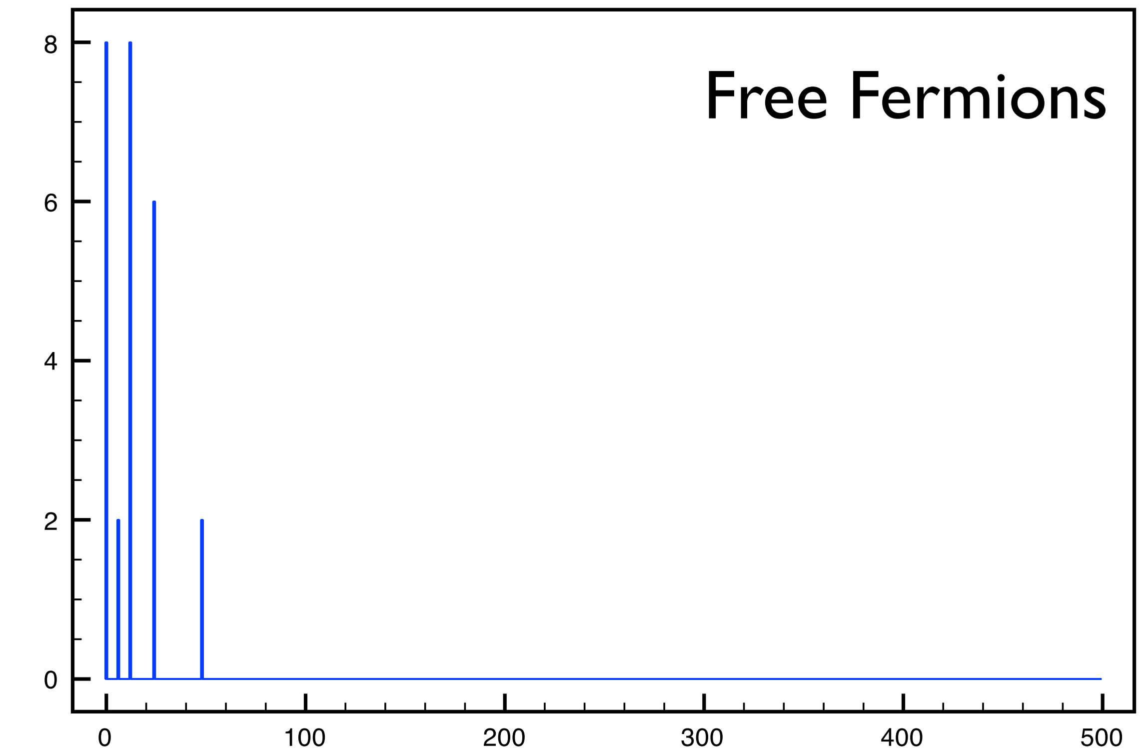
- Free fermion triplets

  Antoniadis, Bachas, Kounnas, Windey (1985)
  Kawai, Lewellyn, Tye (1986); Antoniadis, Bachas, Kounnas (1986)
  Faraggi et. al. (1990 - ....)
  Kiritsis, Lennek, Schellekens (2008)
  Gato-Rivera, Schellekens (2010)

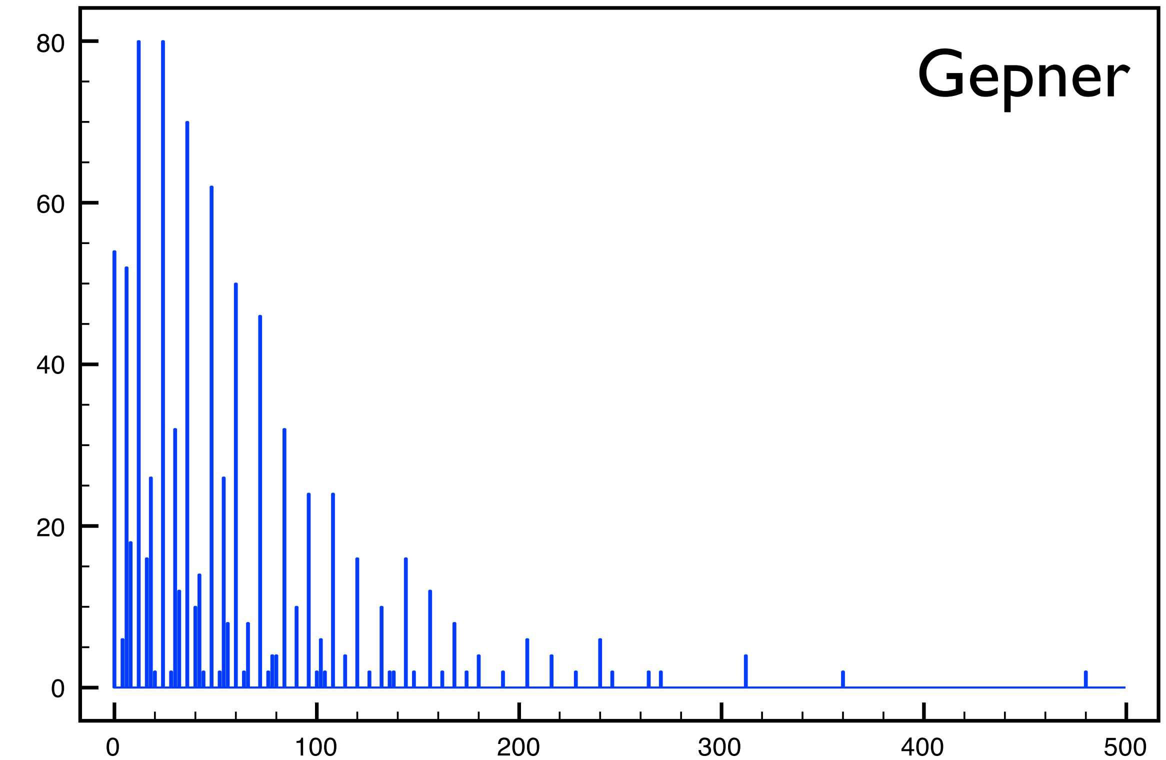
- Permutation orbifolds

  Fuchs, Klemm, Schmidt (1991)
  Maio, Schellekens (2010,2011)

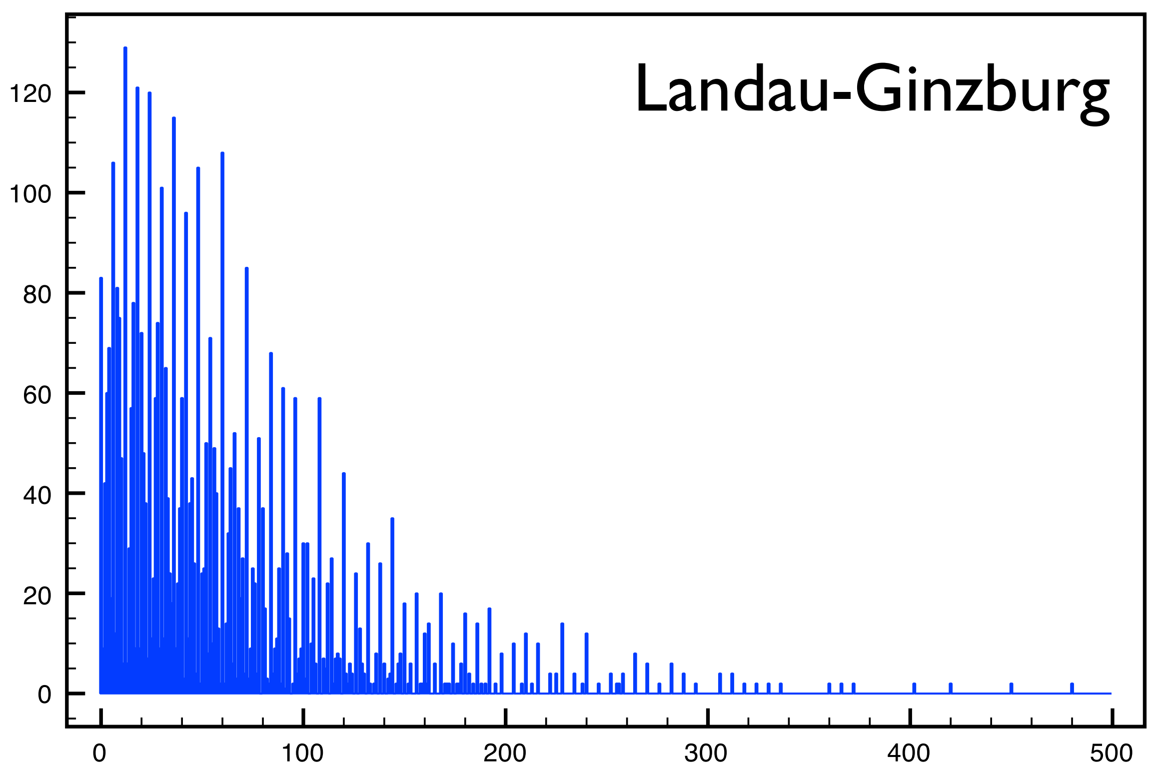
● Tensoring building blocks
● Other methods



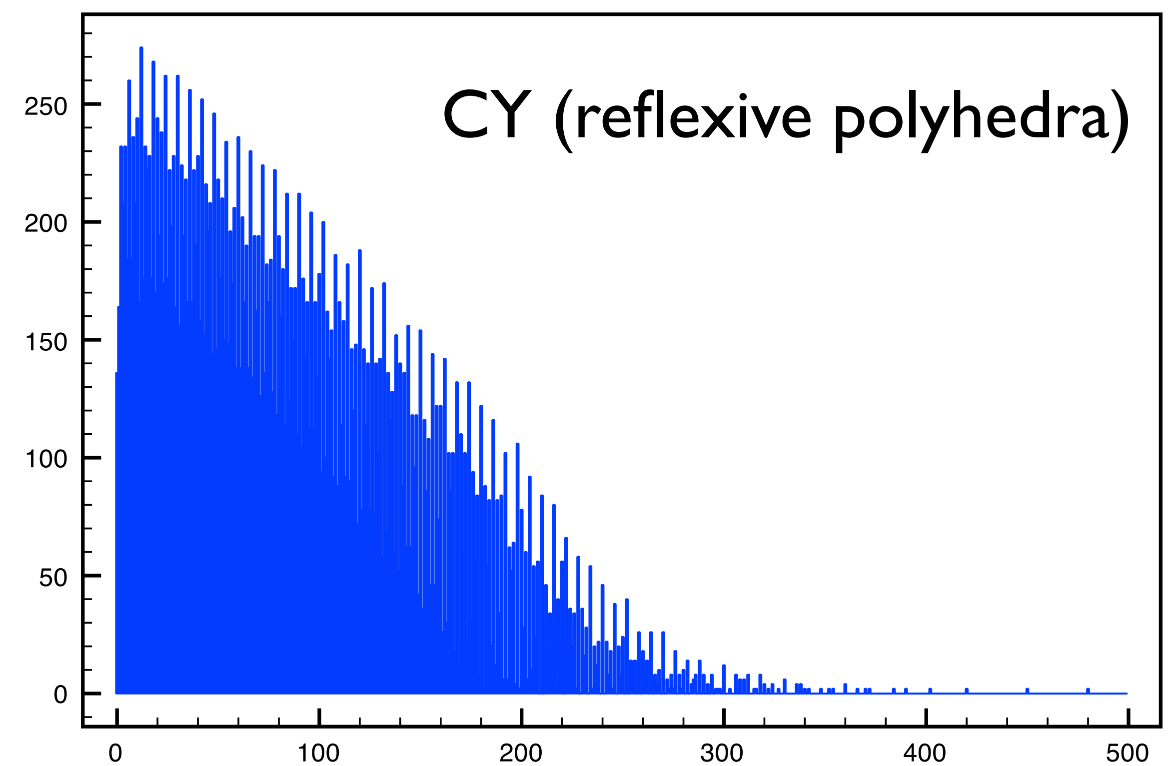
Donagi-Wendland
Kiritsis, Lennek, Schellekens



Schellekens, Yankielowicz
Fuchs, Klemm, Scheich, Schmidt
Gato-Rivera, Schellekens



Kreuzer



Kreuzer, Skarke

Plotted: nr. of distinct Hodge pairs for each number of families

Permutation Orbifolds

Obtained by modding out the permutation symmetry of two identical factors in a CFT

$$\mathcal{A}_{\text{perm}} \equiv \mathcal{A} \times \mathcal{A}/\mathbb{Z}_2$$

Characters:

Off-diagonal		$X_{\langle i,j \rangle}(\tau) = \chi_i(\tau) \cdot \chi_j(\tau)$
Diagonal	$(\xi = 0, 1)$	$X_{(i,\xi)}(\tau) = \frac{1}{2}\chi_i^2(\tau) + e^{i\pi\xi}\frac{1}{2}\chi_i(2\tau)$
Twisted	$(\xi = 0, 1)$	$X_{\widehat{(i,\xi)}}(\tau) = \frac{1}{2}\chi_i(\frac{\tau}{2}) + e^{-i\pi\xi}\, T_i^{-\frac{1}{2}}\, \frac{1}{2}\chi_i(\frac{\tau+1}{2})$

Formula for S

(Borisov, Halpern, Schweigert)

$$
\begin{aligned}
S_{(mn)(pq)} &= S_{mp}\,S_{nq} + S_{mq}\,S_{np} \\
S_{(mn)\widehat{(p,\chi)}} &= 0 \\
S_{\widehat{(p,\phi)}\widehat{(q,\chi)}} &= \frac{1}{2}\,e^{2\pi i(\phi+\chi)/2}\,P_{ip} \\
S_{(i,\phi)(j,\chi)} &= \frac{1}{2}\,S_{ij}\,S_{ij} \\
S_{(i,\phi)(mn)} &= S_{im}\,S_{in} \\
S_{(i,\phi)\widehat{(p,\chi)}} &= \frac{1}{2}\,e^{2\pi i\phi/2}\,S_{ip}\,,
\end{aligned}
$$

$$P = \sqrt{T}ST^2S\sqrt{T}$$

(Sagnotti-Pradisi-Stanev P-matrix;
Betrays orientifold analogy)

Formula for S^J

(work with Michele Maio)

$$\begin{aligned}
S^{(J,\psi)}_{(mn)(pq)} &= S^J_{mp}\, S^J_{nq} + (-1)^\psi S^J_{mq}\, S^J_{np} \\
S^{(J,\psi)}_{(mn)\widehat{(p,\chi)}} &= \begin{cases} 0 & \text{if } J\cdot m = m \\ A\, S_{mp} & \text{if } J\cdot m = n \end{cases} \\
S^{(J,\psi)}_{\widehat{(p,\phi)}\widehat{(q,\chi)}} &= B\, \frac{1}{2}\, e^{i\pi \hat{Q}_J(p)}\, P_{Jp,q}\, e^{i\pi(\phi+\chi)} \\
S^{(J,\psi)}_{(i,\phi)(j,\chi)} &= \frac{1}{2}\, S^J_{ij}\, S^J_{ij} \\
S^{(J,\psi)}_{(i,\phi)(mn)} &= S^J_{im}\, S^J_{in} \\
S^{(J,\psi)}_{(i,\phi)\widehat{(p,\chi)}} &= C\, \frac{1}{2}\, e^{i\pi\phi}\, S_{ip}\,.
\end{aligned}$$

$\psi = \pm 1$

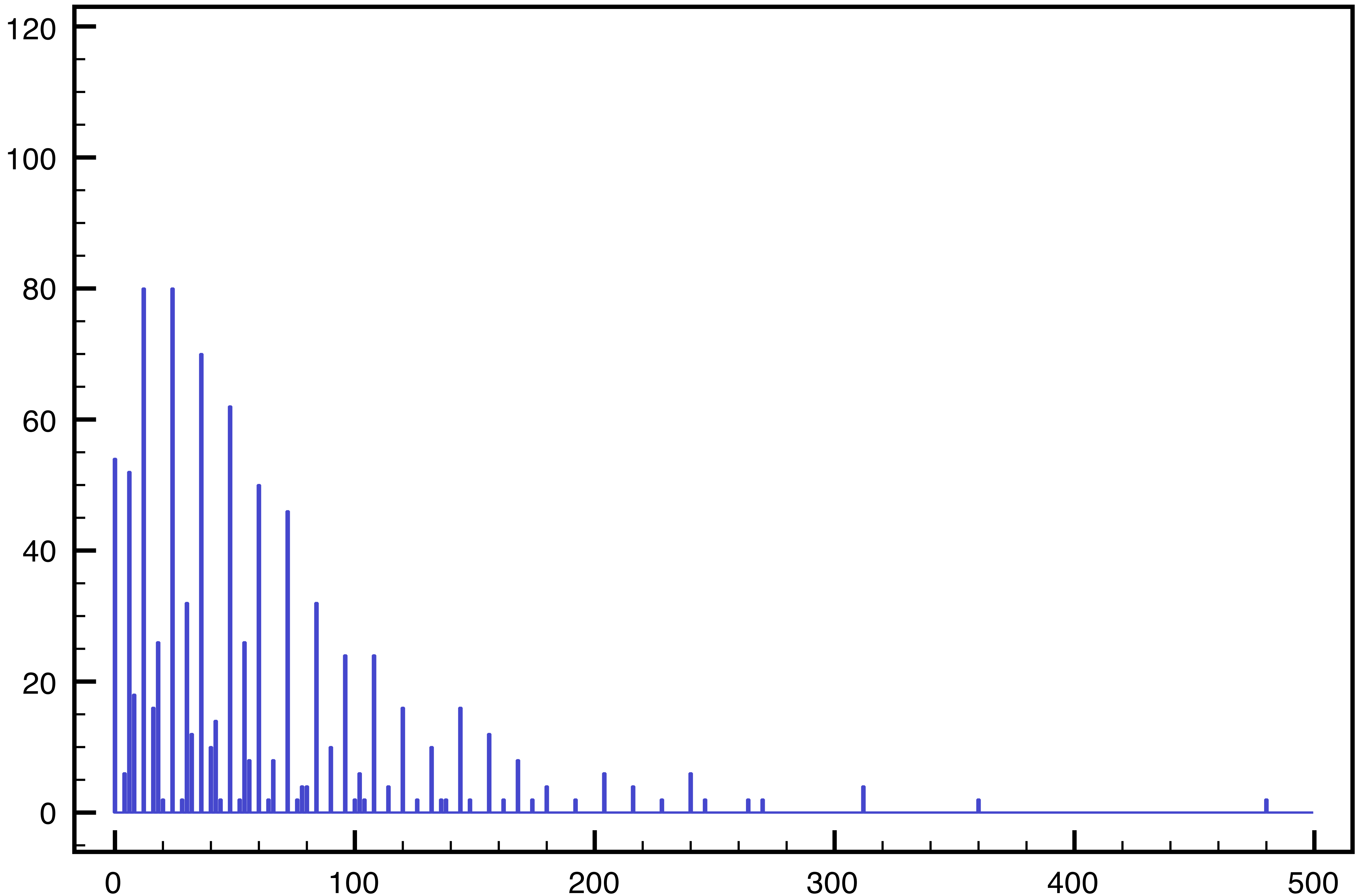
$B, C = \pm 1$ (“gauge” choices)

Applied to N=2 CFTs

$$
\begin{tikzcd}[column sep=huge, row sep=huge]
\boxed{(N=2)^2} \arrow[r, "T_F \otimes T_F"] \arrow[d, shift left, "BHS"] & \boxed{(N=2)^2_{Susy}} \arrow[d, Rightarrow, shift left, "super-BHS"] \\
\boxed{(N=2)^2_{orb}} \arrow[r, "{(T_F,1)}"] \arrow[u, dotted, shift left, "{(0,1)}"] & \boxed{(N=2)^2_{Susy-orb}} \arrow[u, dotted, shift left, "{(0,1)}"]
\end{tikzcd}
$$

Fixed point
resolution required

Results can be compared with work by *Fuchs, Klemm, Schmidt (1992)*



120
100
80
60
40
20
0
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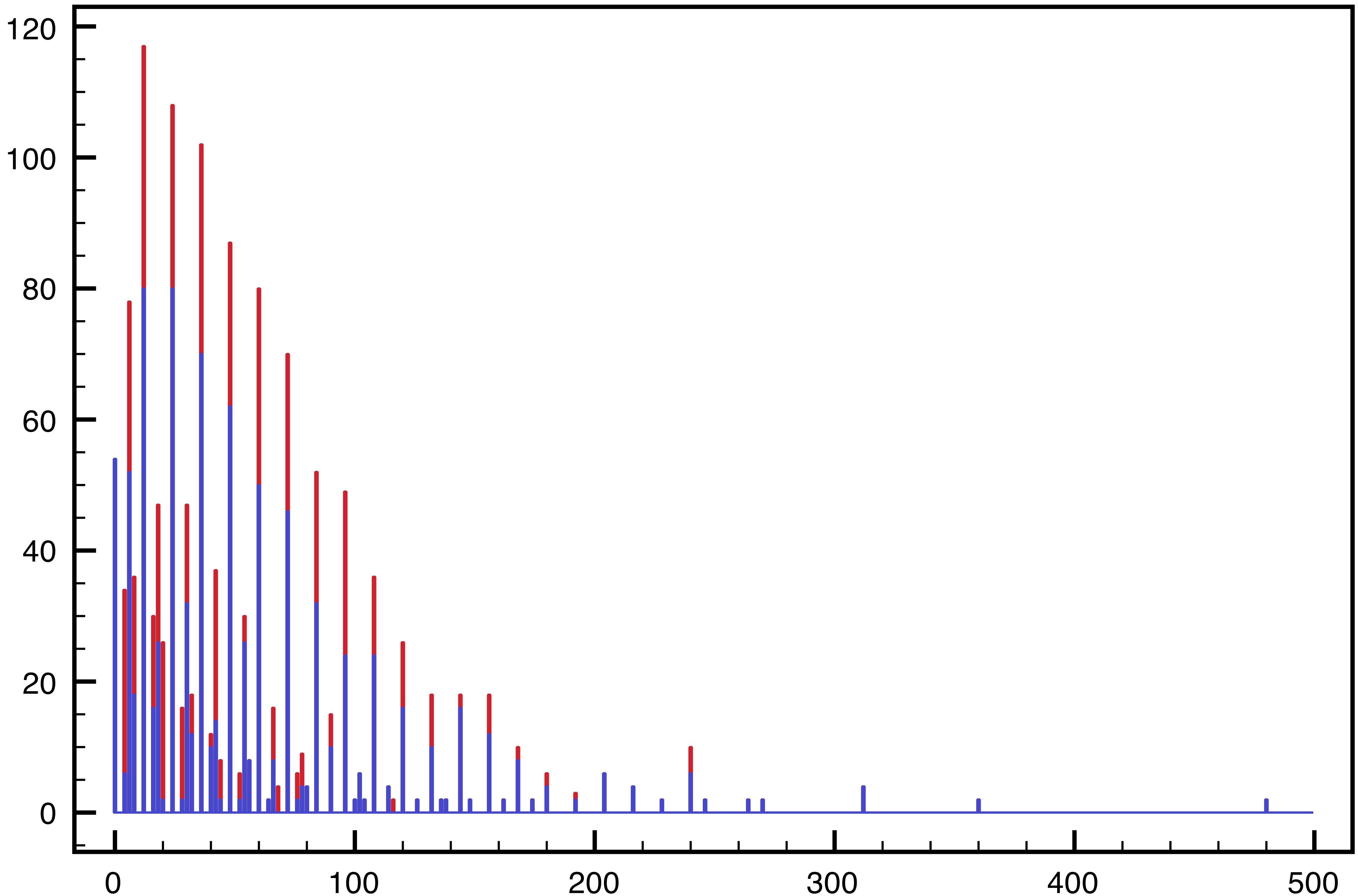
100
200
300
400
500



120
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500

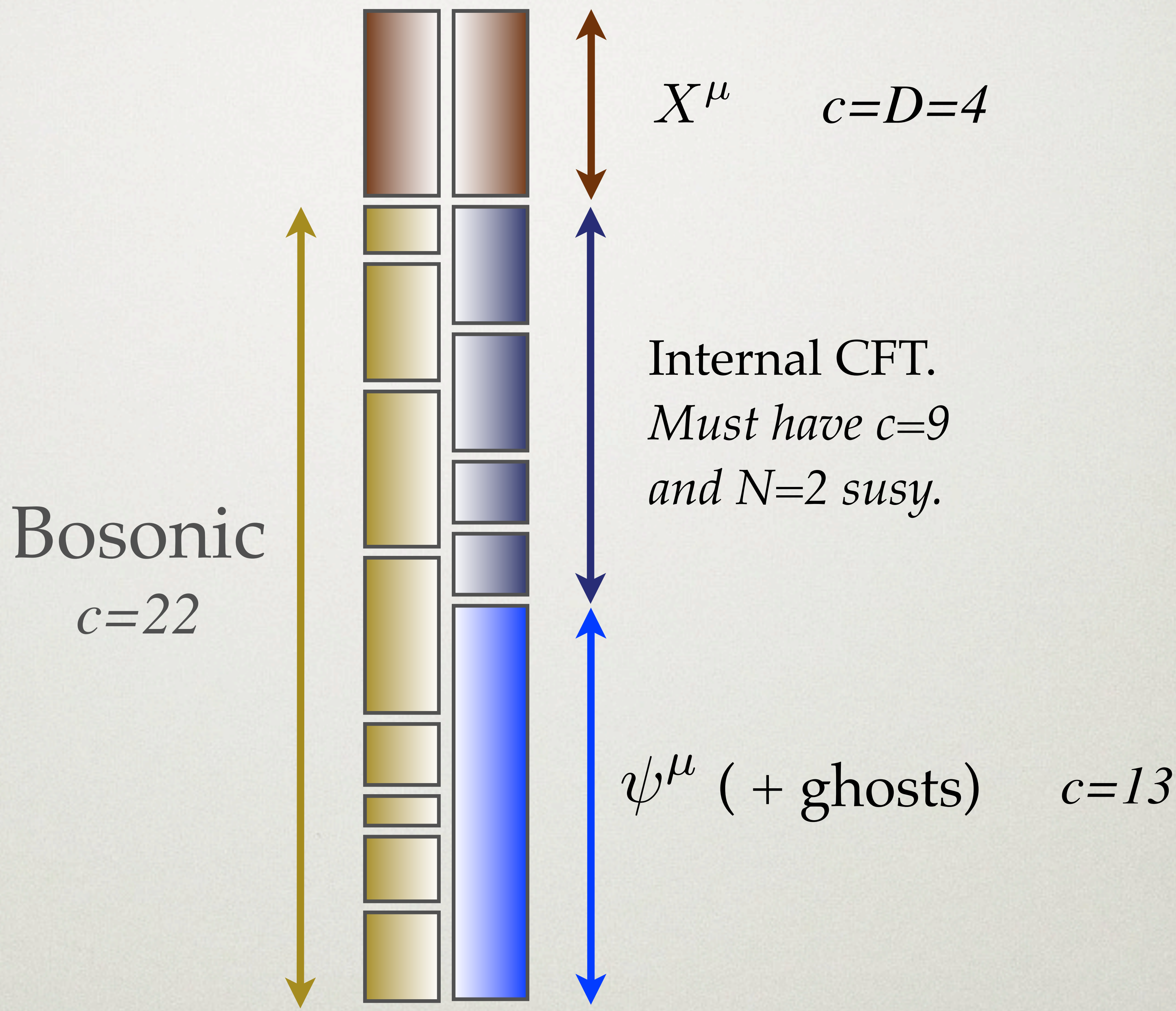
Heterotic Strings

Other approaches:

Free Fermions
(Asymmetric) Orbifolds, "Mini-Landscape",
Geometric constructions

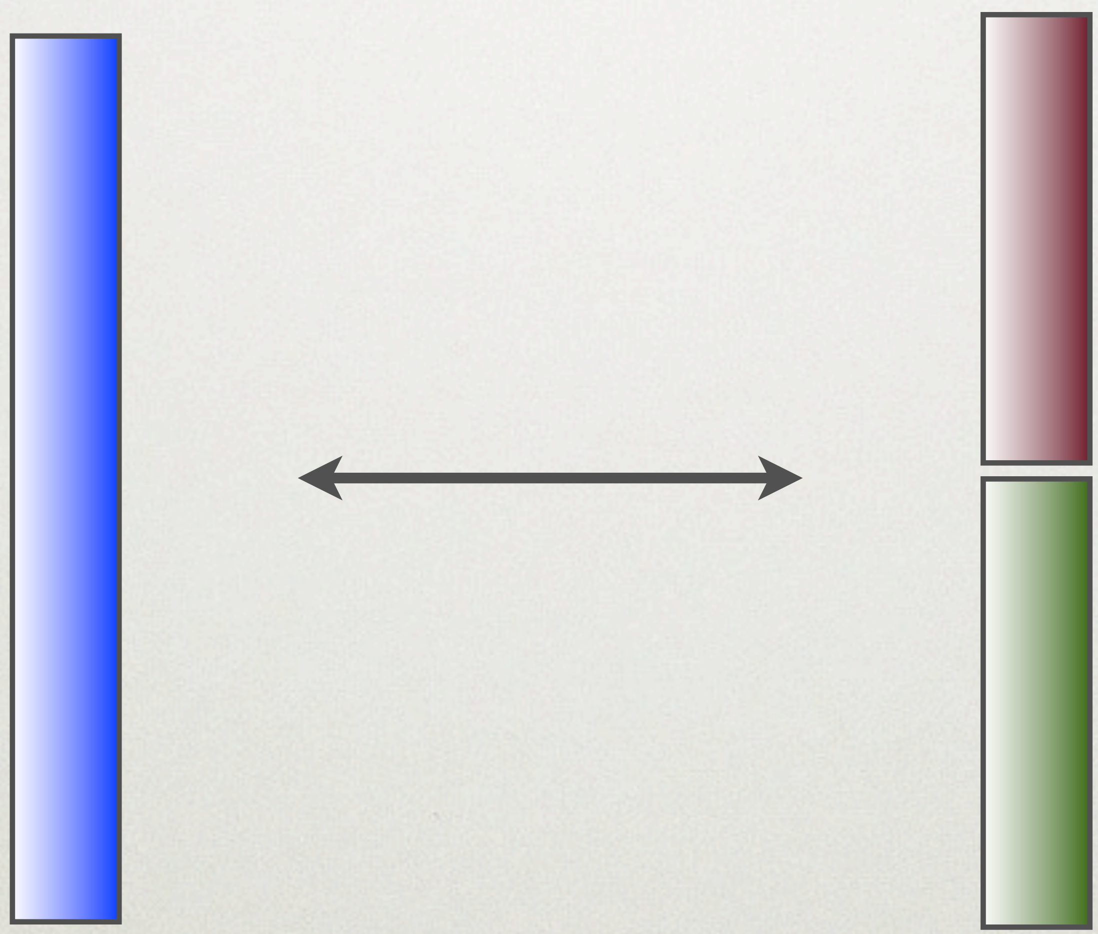
Several talks in this meeting

Heterotic strings



The Bosonic String Map

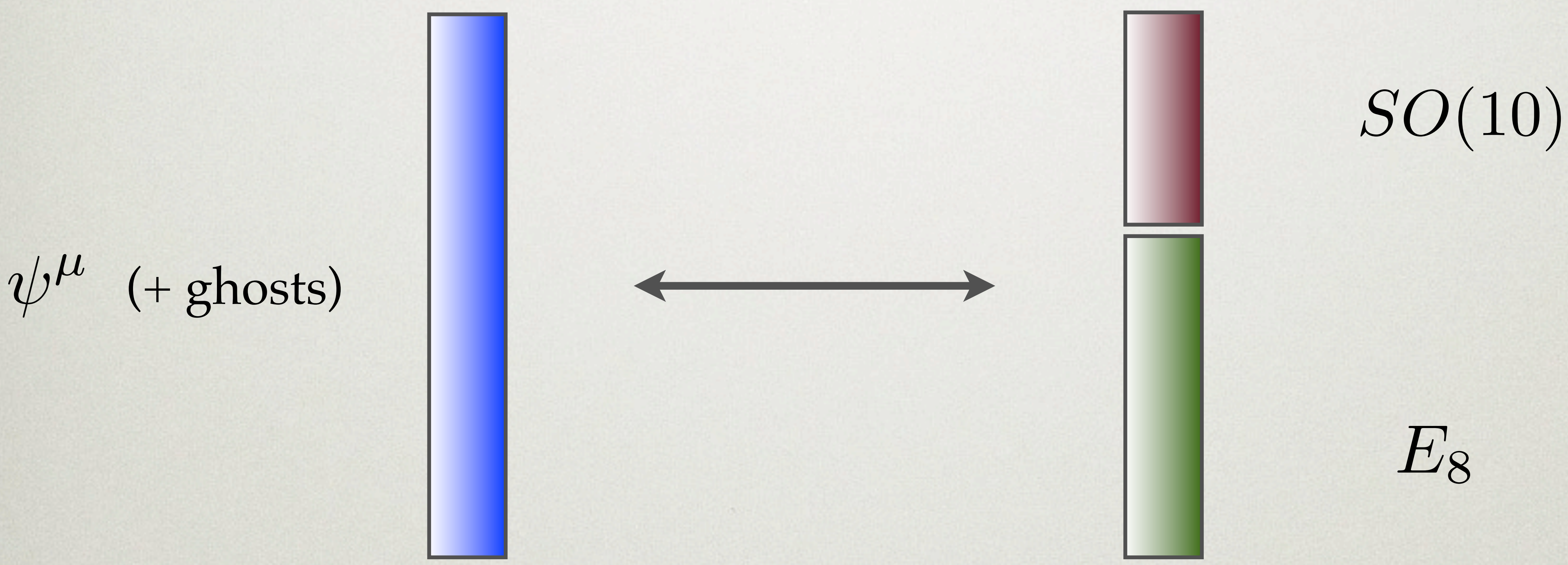
Modular invariance restricts this severely.
Solutions exist because of isomorphisms between modular group representations.



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

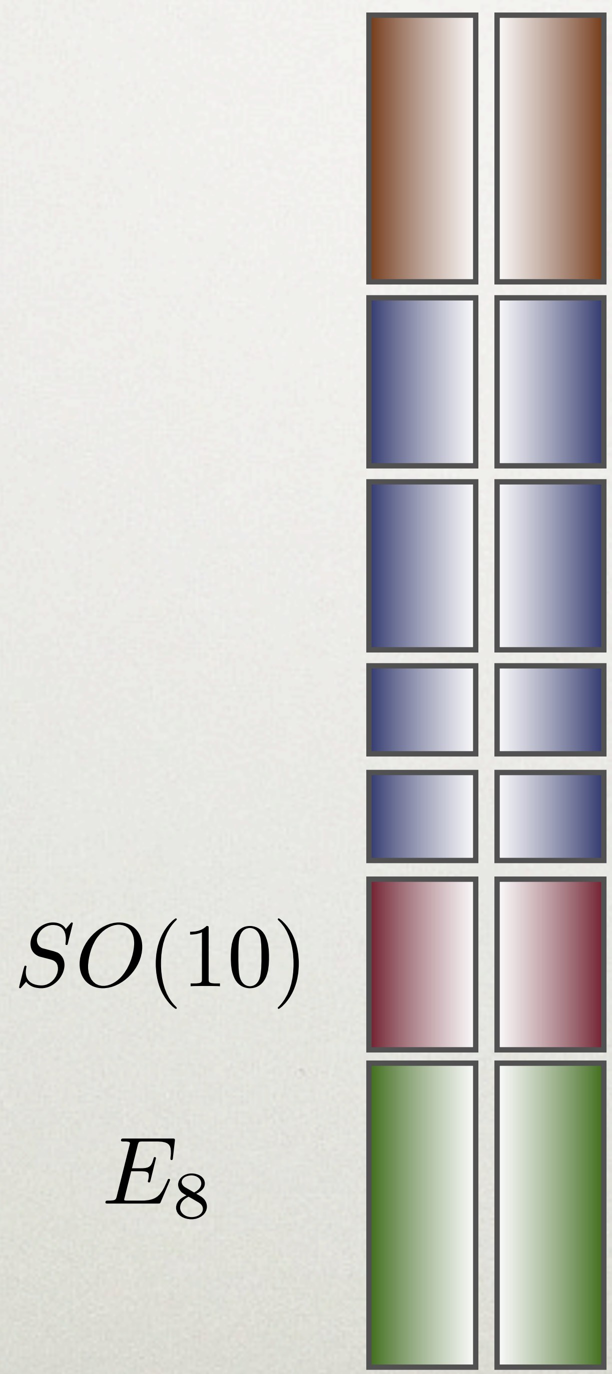
The Bosonic String Map

This also works in 4 dimensions:

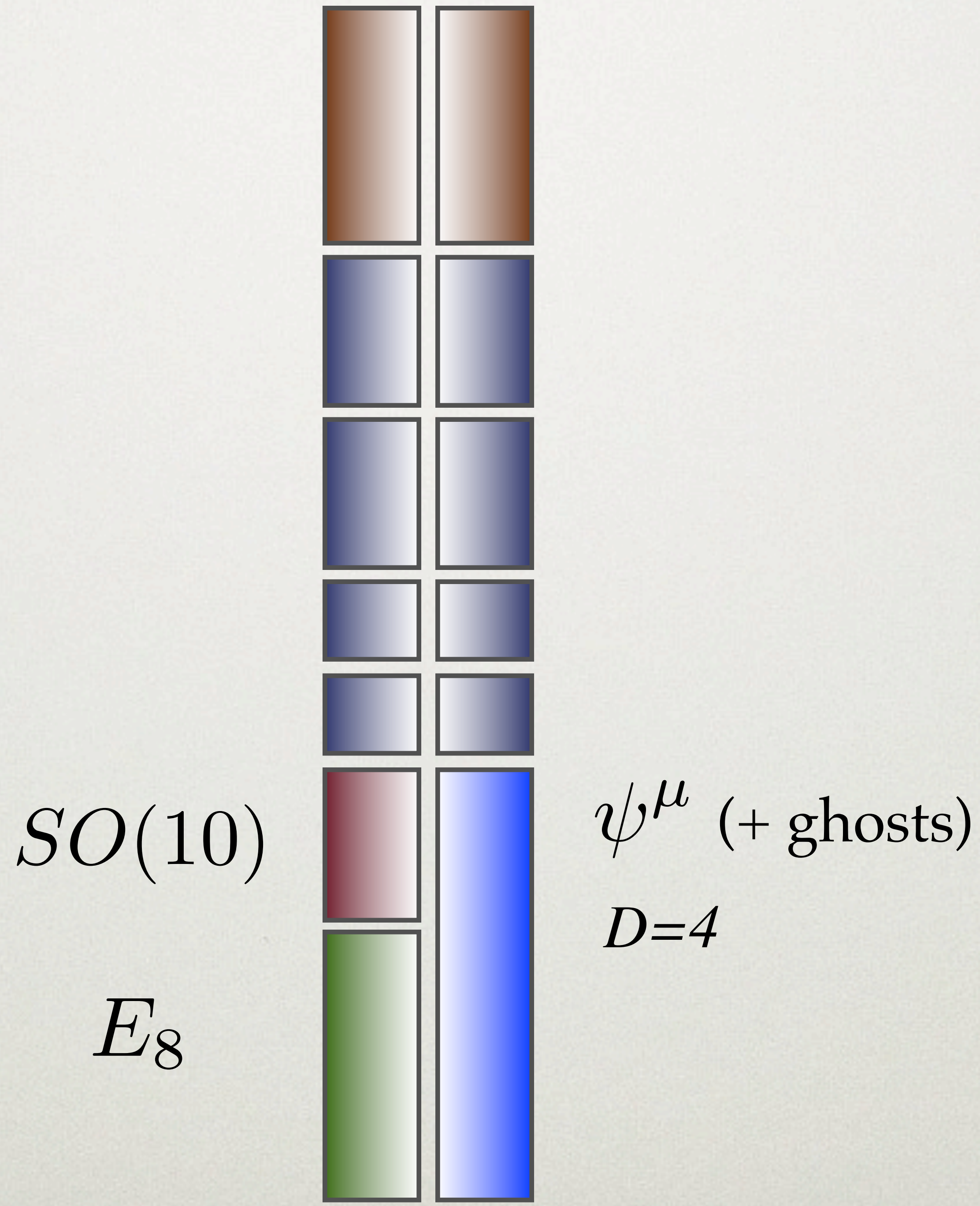


Lerche, Lüst, Schellekens (1986)

Start with an especially prepared bosonic string...



... and map it to a heterotic string



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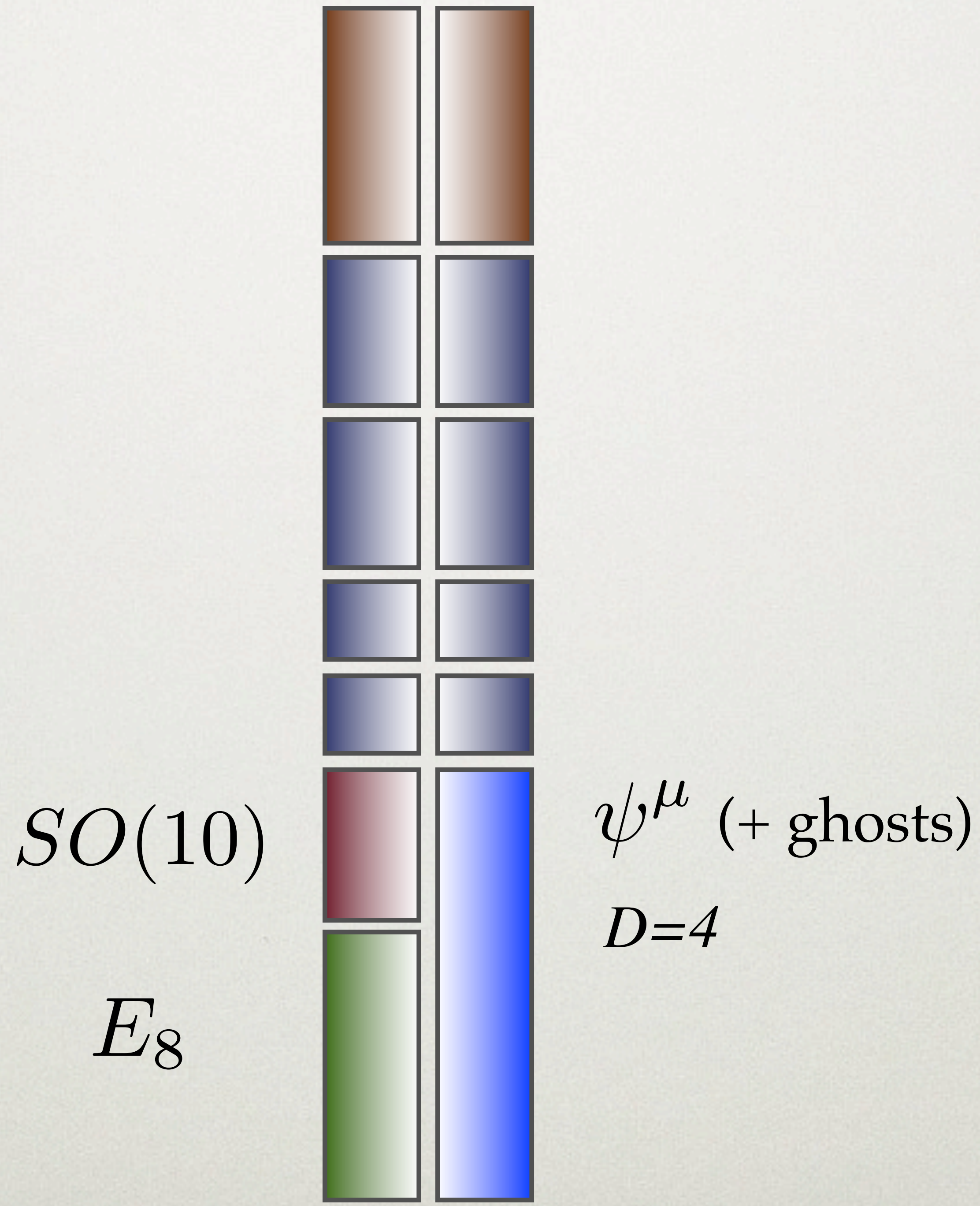
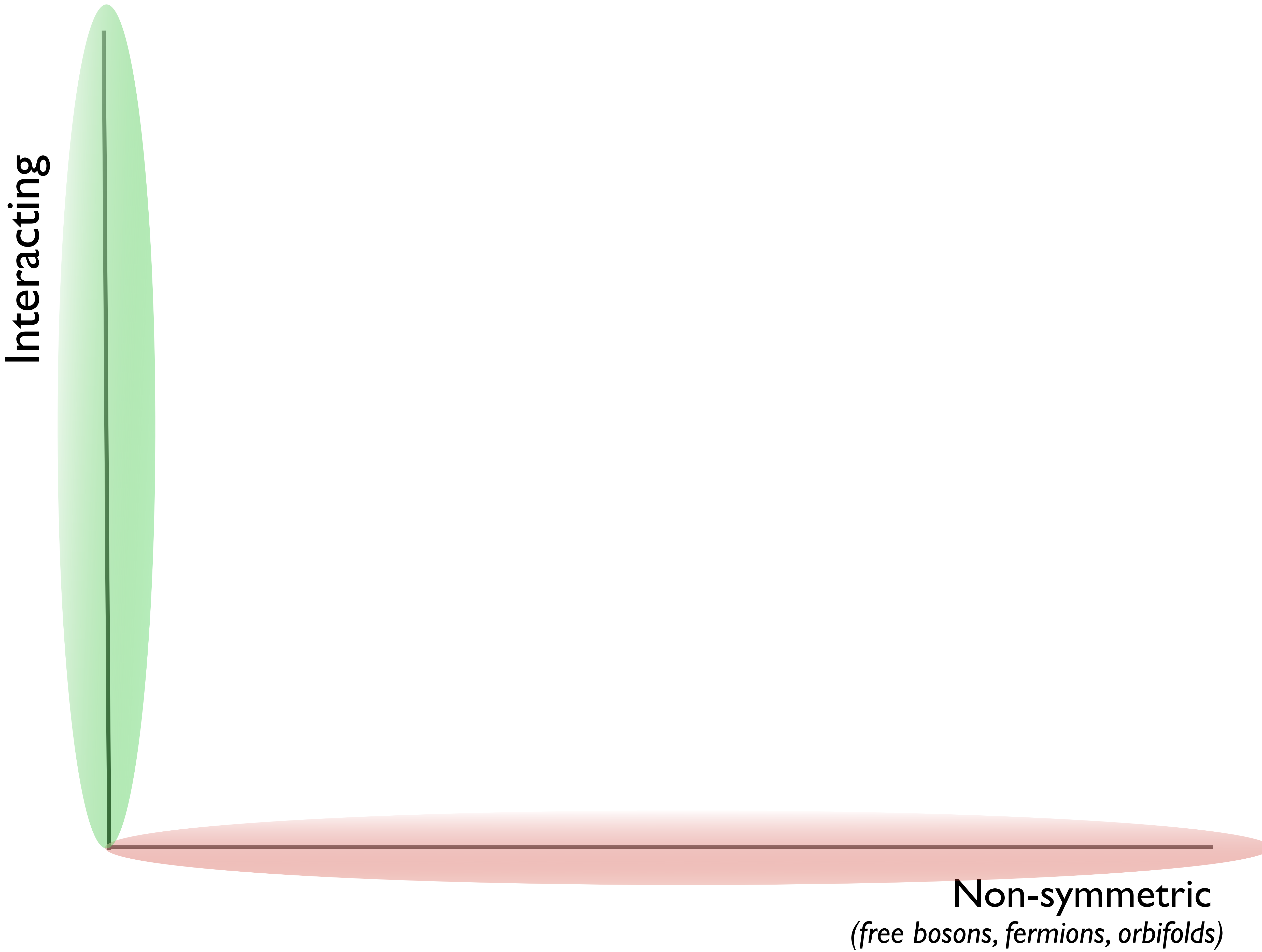
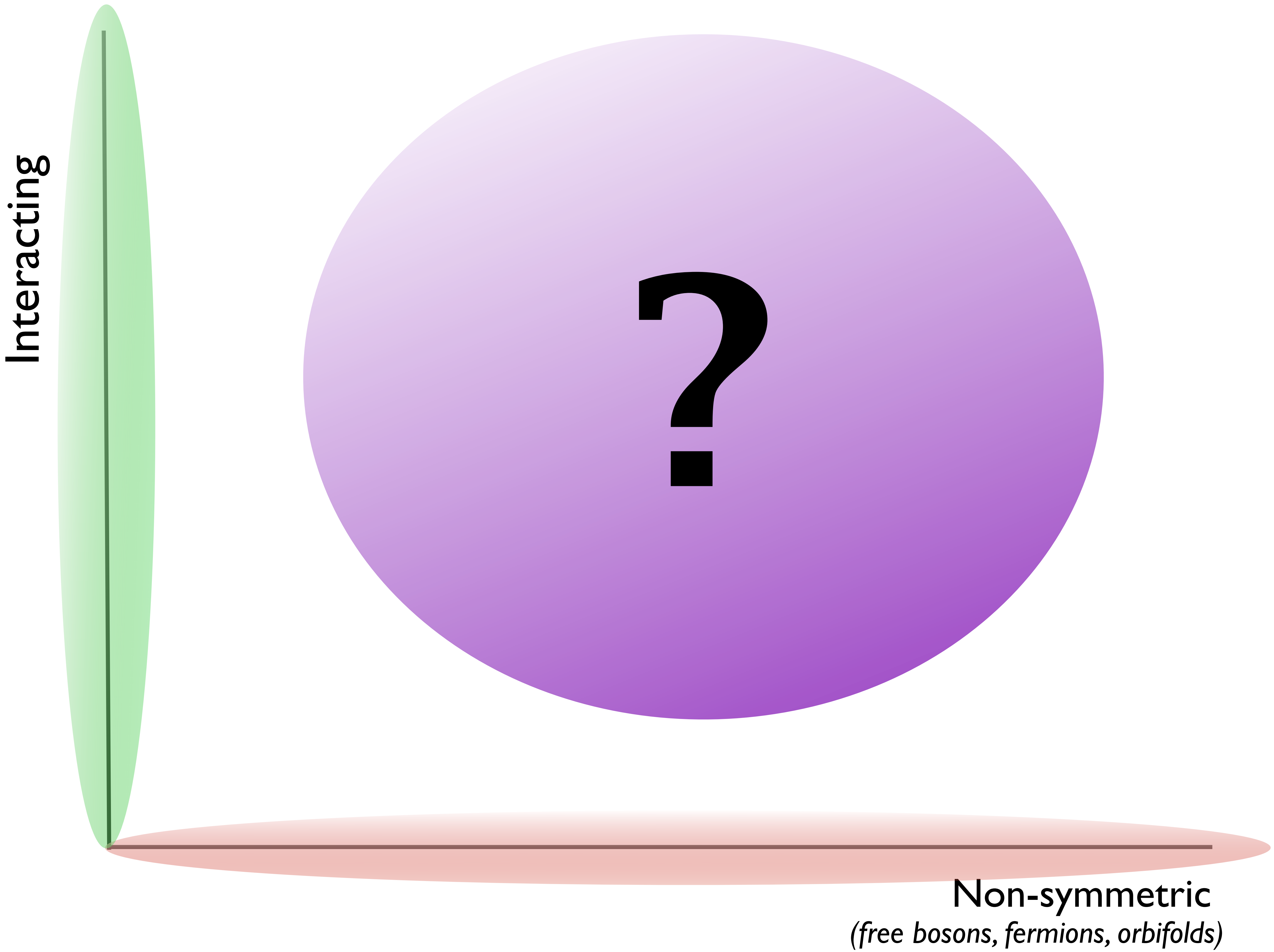


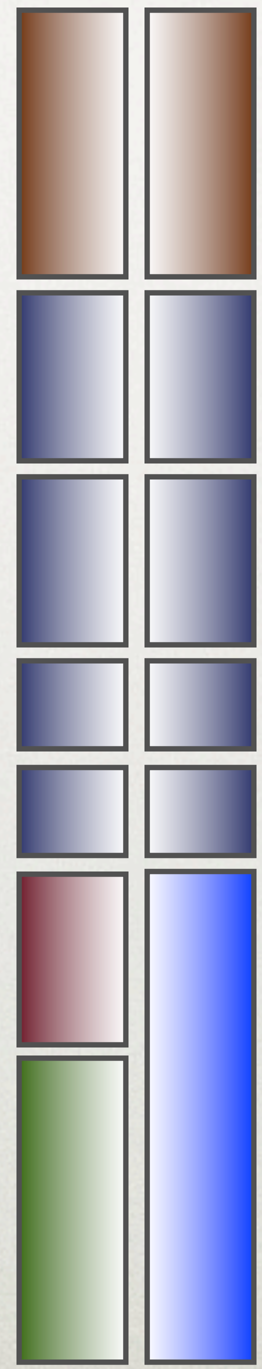
Families of (16)'s of SO(10)!


Interacting
Non-symmetric
(free bosons, fermions, orbifolds)


Interacting
?
Non-symmetric
(free bosons, fermions, orbifolds)

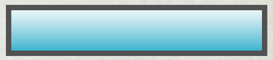
Imposing space-time supersymmetry

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



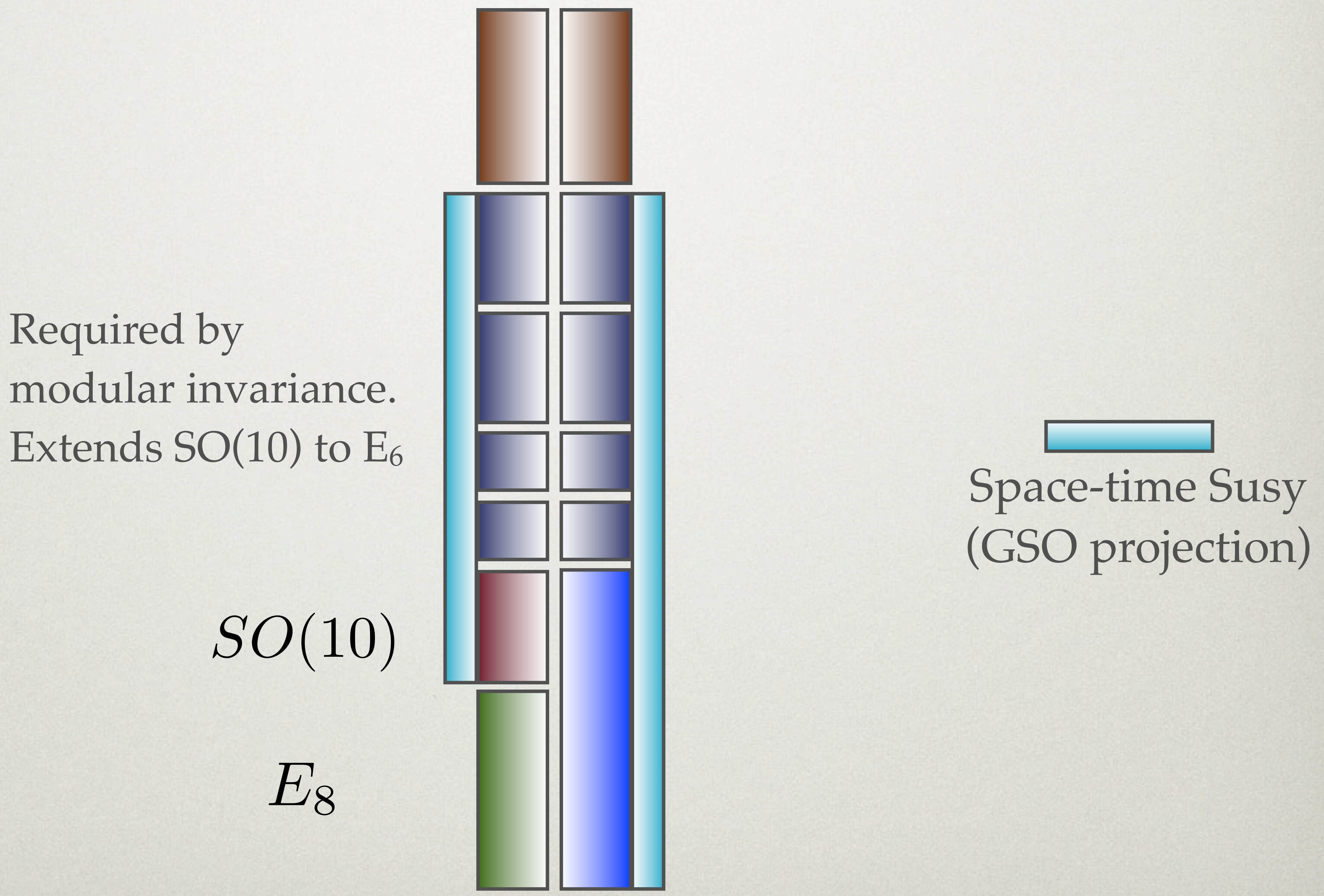
$SO(10)$

E_8



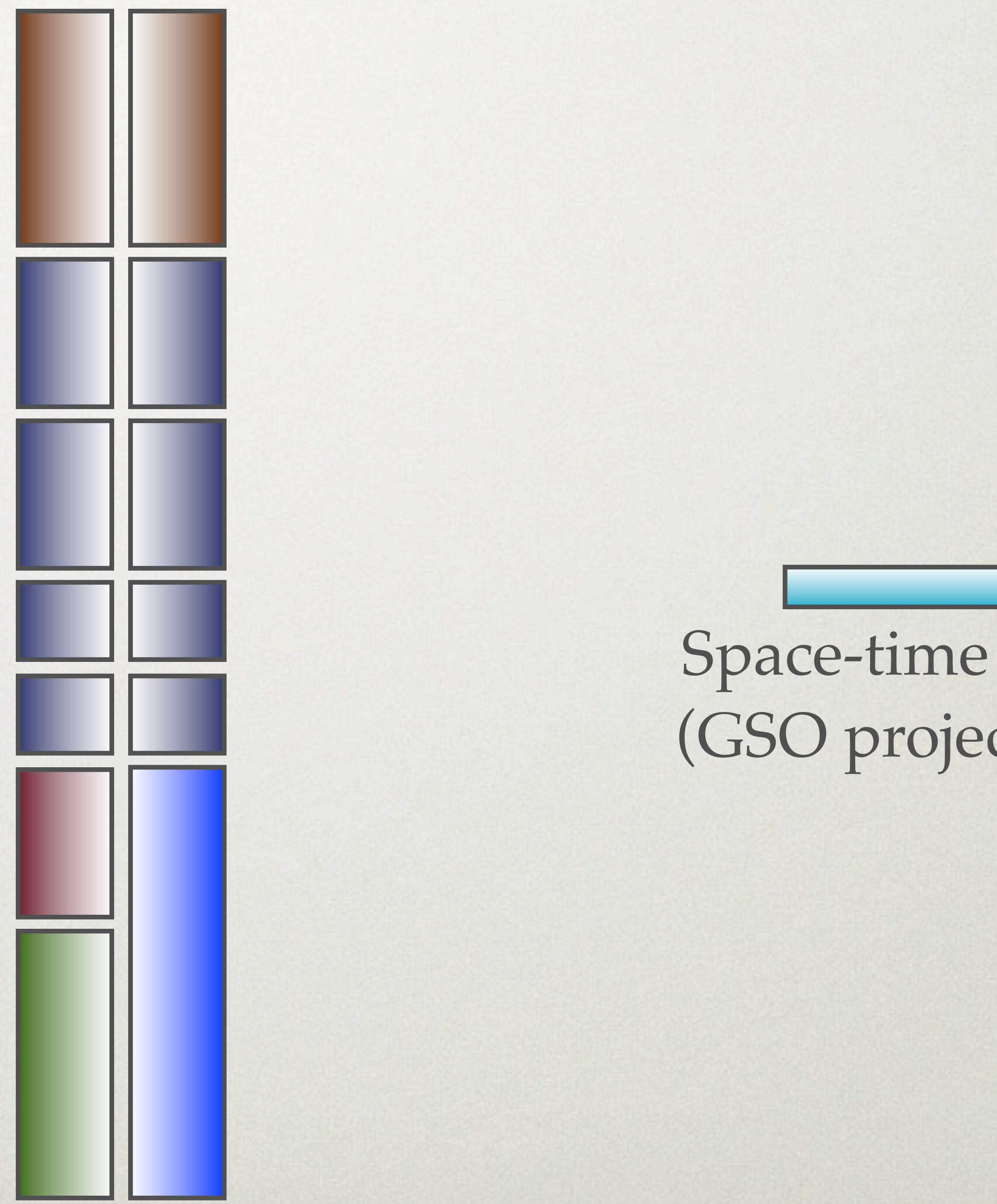
Space-time Susy
(GSO projection)

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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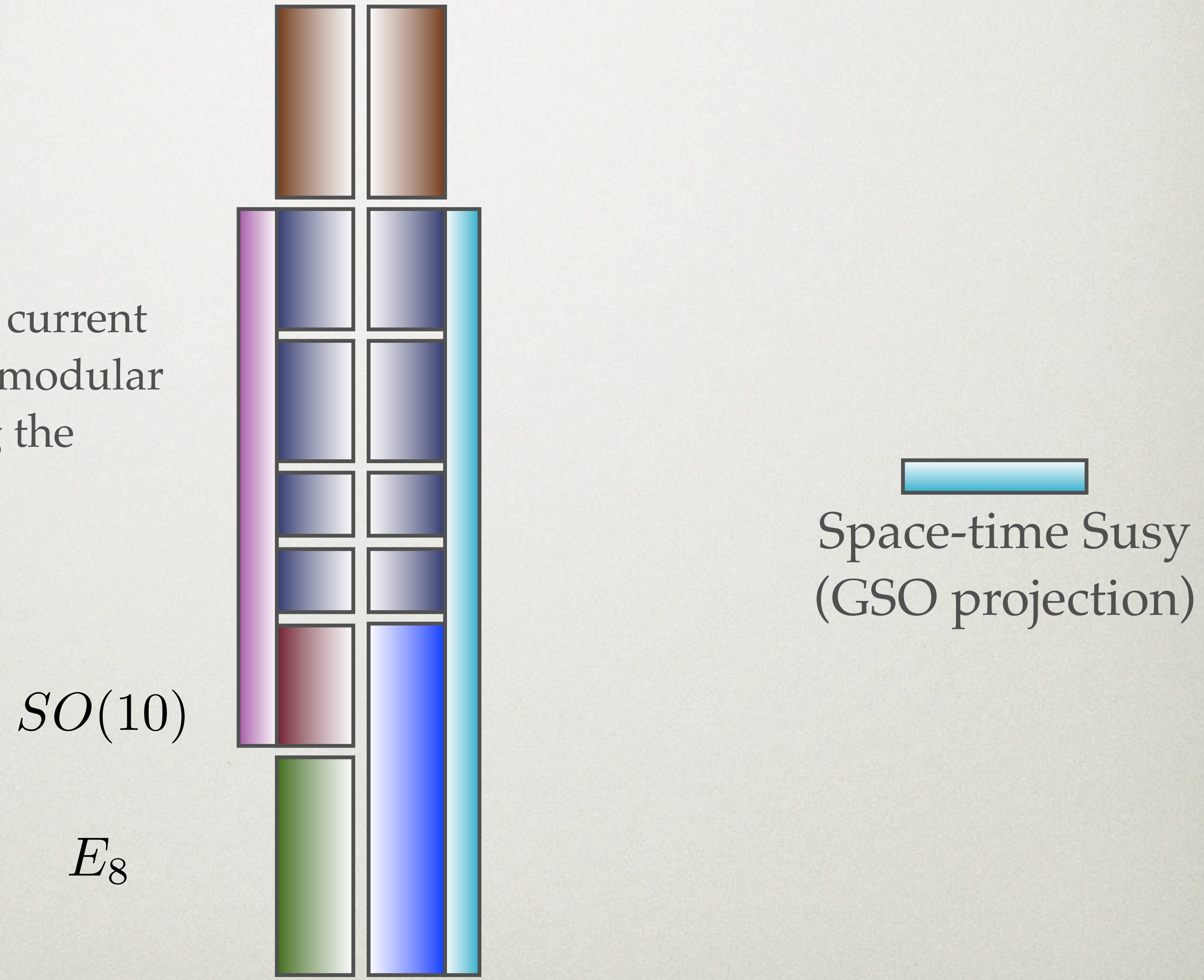
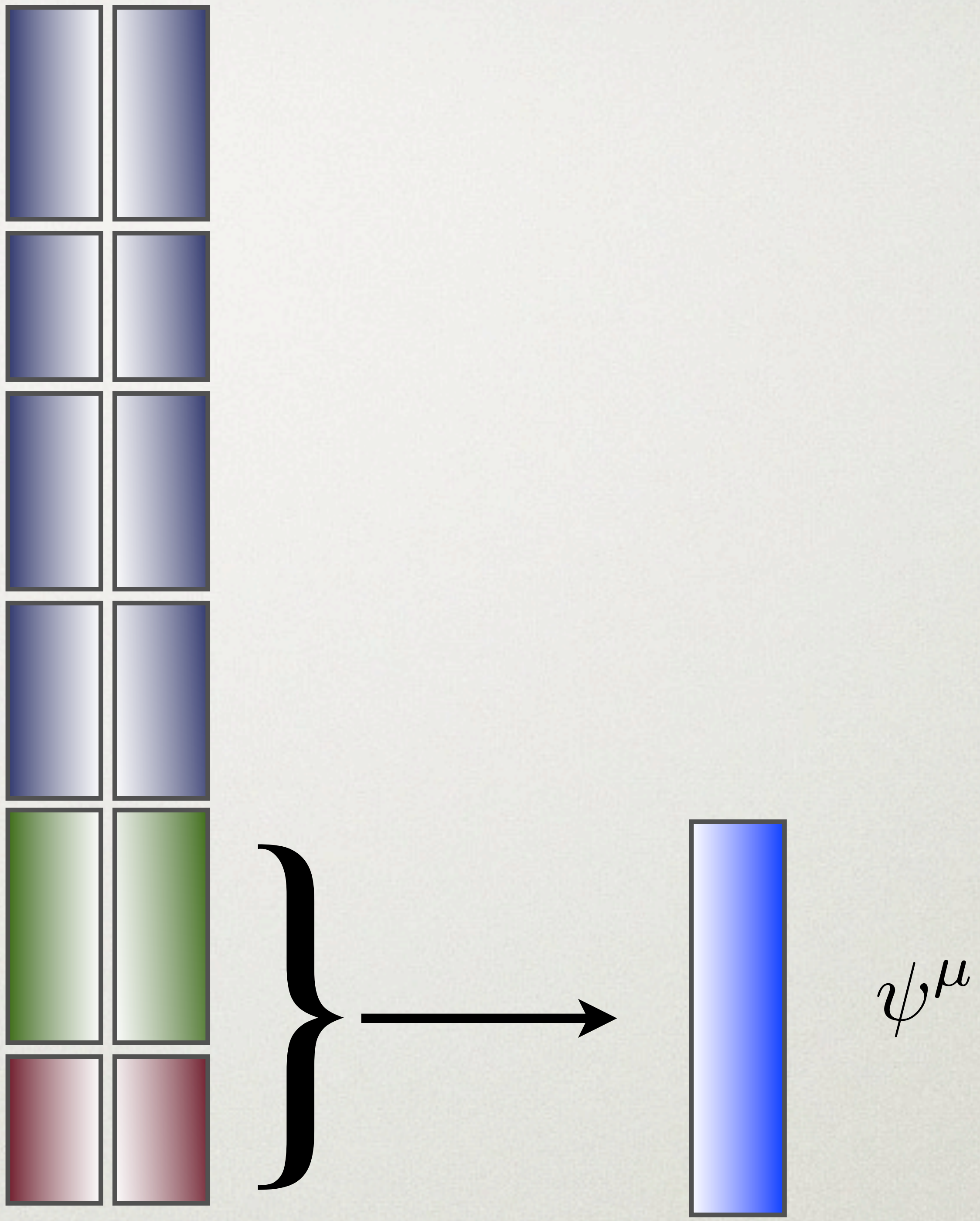
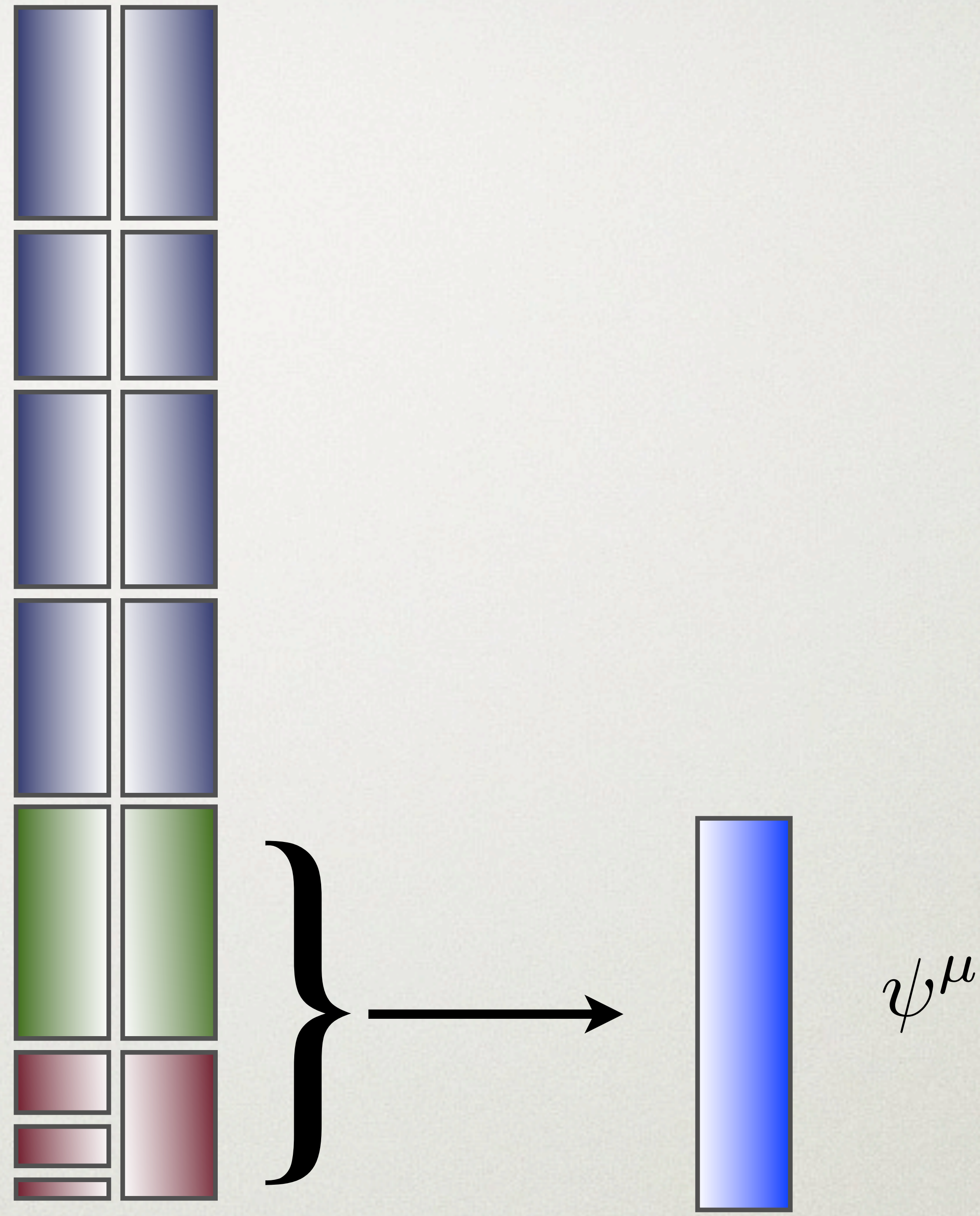


Schellekens, Yankielowicz (1989)


ψ^μ

SO(10) currents replaced by operators of higher weight



Gauge group H $\subset$ SO(10)

Breaking SO(10)

Consider $SU(3) \times SU(2) \times U(1)_{30} \times U(1)_{20} \subset SO(10)$ [$U(1)_N$ has N primaries]

Y B-L

This gives standard gauge coupling unification.
Common to all "classic" heterotic string constructions*.

$U(1)_{30}$ allows Y-charges $-\frac{15}{6}, \ldots, +\frac{15}{6}$

In the massless spectrum only a subset of these can occur: $h_{SU(3)} + h_{SU(2)} + \frac{3}{5} Y^2 \leq 1$

This allows precisely all the Standard Models charges, including those of the GUT X,Y bosons, but also many fractionally charged representations.

(*) Orbifolds, "heterotic mini-landscape", Free fermion constructions (Faraggi et. al.), most Calabi-Yau compacifications, Gepner models, ...

Half-integer or third-integer charges can be avoided by clever choices of the CFT, but not simultaneously.

Absence of ALL fractional charges ⇔ Extension to **unbroken** SU(5) GUT

(A.N. Schellekens, Phys. Lett. B237, 363, 1990).
Related results: Wen and Witten, Nucl. Phys. B261, 651 (1985); Athanasiu, Atick, Dine, Fischler, Phys. Lett. B214, 55 (1988)

Possible ways out:
Fractional charges could be massive, vector-like (and liftable) or confined by some additional gauge group.

Possible way out in CFT:
Standard Model particles are associated with internal sector Ramond ground states, which must always be present, and whose conformal weight is fixed.
Fractionally charged particles are related to other primaries, which must be present in order to be able to break SO(10), but their weights can vary by integers.
So finding a suitable N=2 CFT would do the trick for (2,2)-related spectra.

But: this argument is not valid in (0,2) CFT's.

SO(10) CFT sub-algebras

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

Fractional charges in Orientifold models

SM-realizations with at most four branes*

Non-orientable "x=½"

Half-integer charges in hidden sector (if present)

Non-orientable "x=0"

Only integer charges in perturbative spectrum

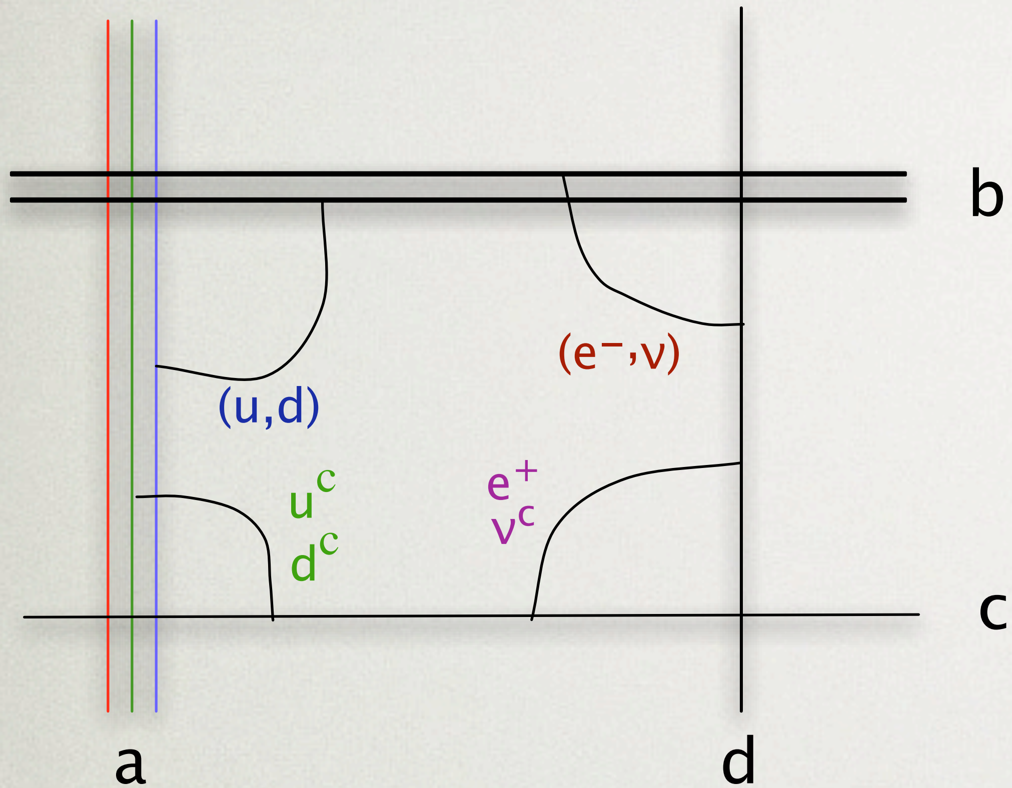
Orientable

±x integer charges in hidden sector (if present)

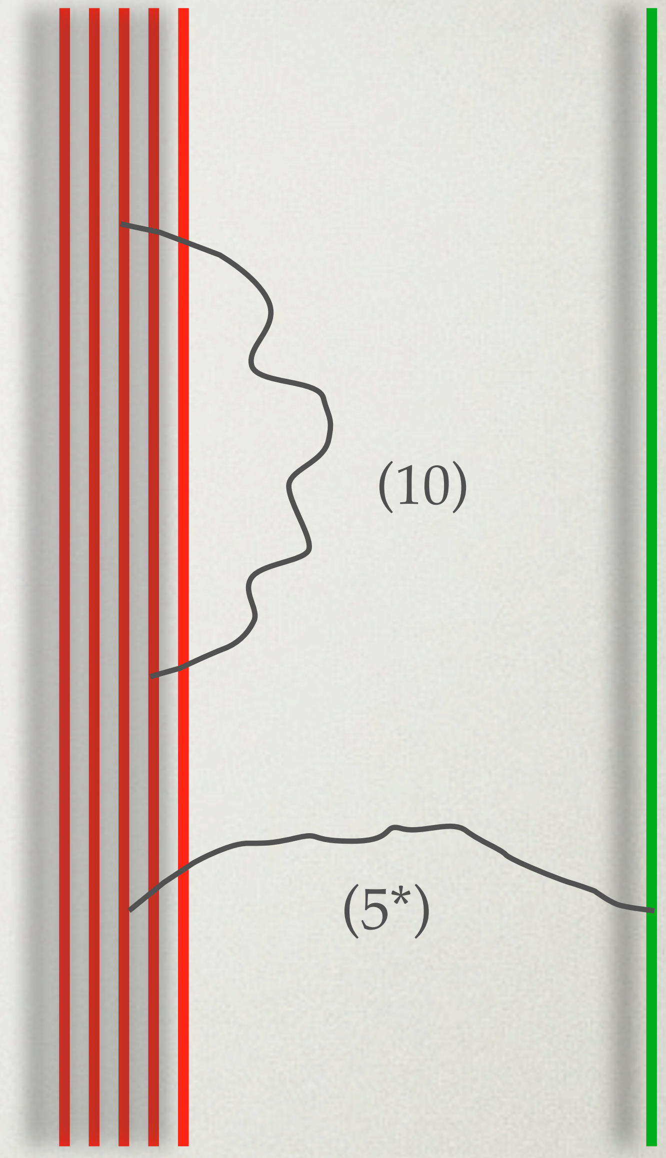
No fractional charges in SM-realizations with few branes.

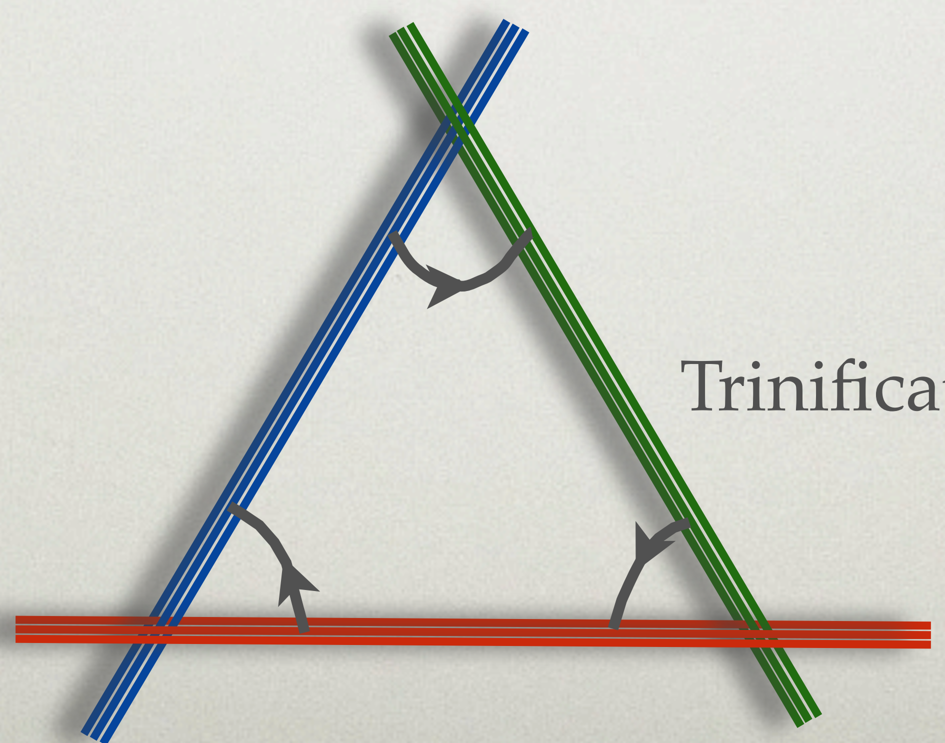
(*) Anastasopoulos, Dijkstra, Kiritsis, Schellekens

"Madrid Model"



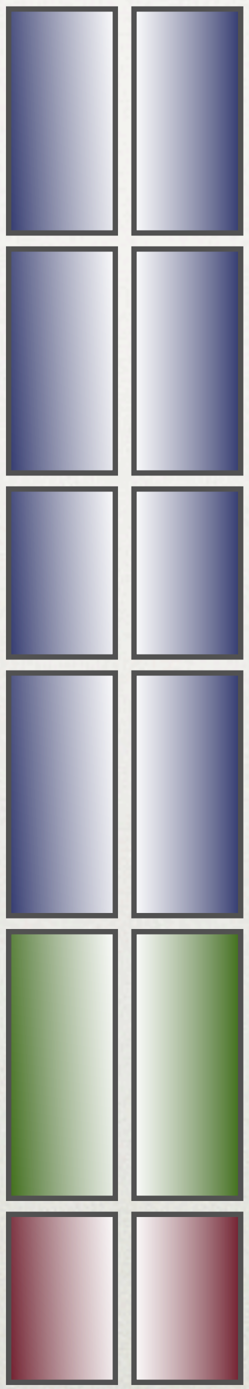
SU(5)





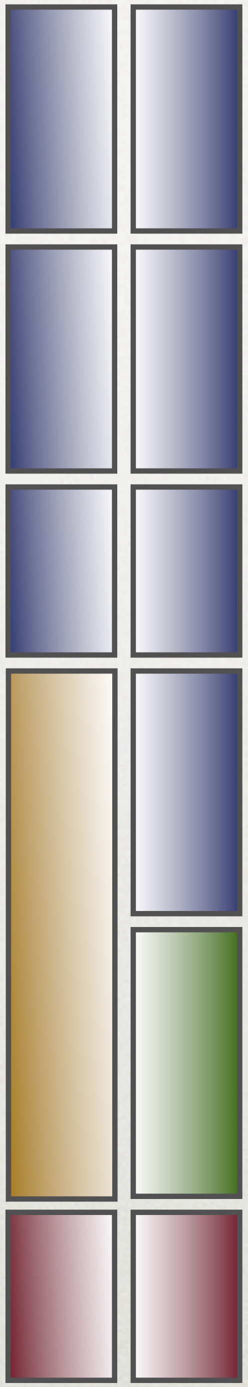
Trinification

Heterotic Weight Lifting



Gato-Rivera, Schellekens, 2009

Heterotic Weight Lifting



Gato-Rivera, Schellekens, 2009

Minimal N=2 model at level k: $c = \dfrac{3k}{k+2}$

Coset description:

$$\frac{SU(2)_k \times SO(2)}{U_{k+2}}$$

Plus “field identification”

Remove the (formal) field identification extension, and consider

$$SU(2)_{k+2} \times SO(2) \times \frac{E_8}{U_{k+2}}$$

In other words, we embed the U(1) in E_8 instead of SU(2) x SO(2).

Next we identify a CFT X_7 which can be combined with U_{k+2} to E_8, so that

$$E_8 = [U_{k+2} \times X_7]_{\text{ext}}$$

Then we can write the CFT as

$$SU(2)_{k+2} \times SO(2) \times X_7$$

And finally we re-establish the equivalent of the field identification, as a standard, higher spin extension

The result is guaranteed, by construction, to have the same S and T matrices as the original minimal model.

But the spectrum is different

Standard coset field $\quad h_i^G - h_j^H \qquad (j \in i)$

Replacement $\quad h_i^G + h_j^{H^c}$

$$h_j^{H^c} = -h_j^H \mod 1$$

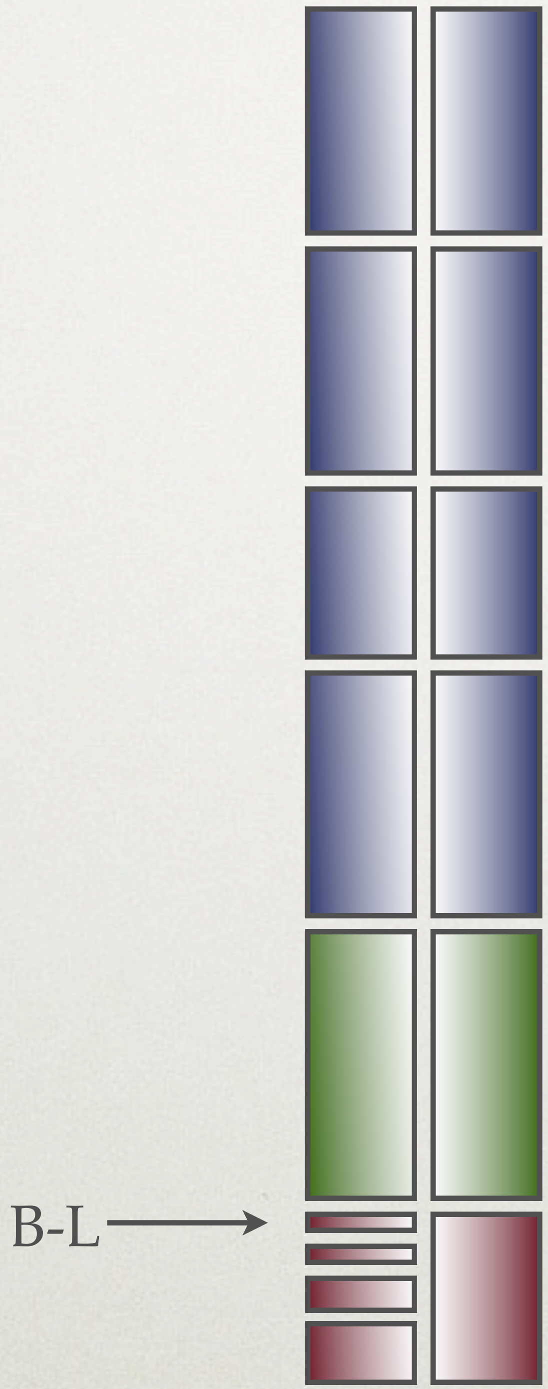
All weight of H and H^c are positive
Therefore standard weights are lifted:

$$h_i^G + h_j^{H^c} > h_i^G - h_J^H$$

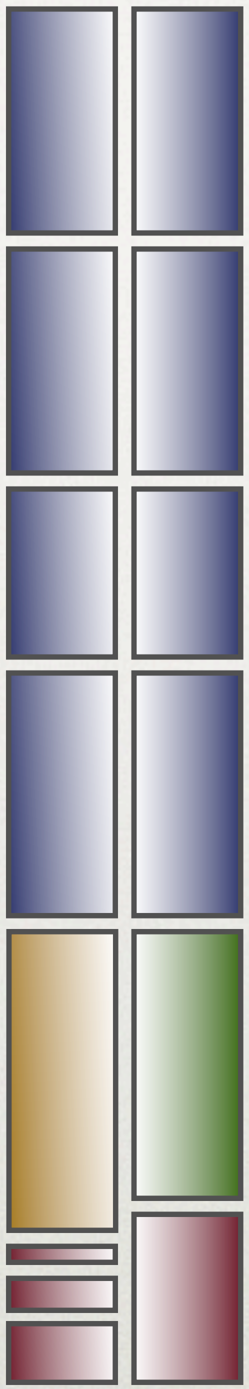
(but equal mod 1)

k	Lift	Lifted	Lowered	Unchanged
1	$E_6 \times A_1$	4	1	4
2	A_7	7	1	12
3	$[D_6 \times U_{10}]_{\text{ext}}$	10	3	22
4	$D_5 \times A_2$	21	4	23
5	$A_6 \times A_1$	32	8	29
5	$[E_6 \times U_{42}]_{\text{ext}}$	24	11	37
6	$[A_6 \times U_{112}]_{\text{ext}}$	33	15	39
8	$A_4 \times A_3$	65	29	37
9	$[A_6 \times U_{154}]_{\text{ext}}$	76	41	39
11	$[E_6 \times U_{78}]_{\text{ext}}$	104	61	39
11	$[D_6 \times U_{26}]_{\text{ext}}$	98	60	45
12	$A_6 \times U_4$	125	66	39
13	$A_4 \times A_2 \times A_1$	136	81	37
14	$[A_4 \times A_2 \times U_{480}]_{\text{ext}}$	147	105	47
14	$[A_6 \times U_{224}]_{\text{ext}}$	153	95	41
17	$[E_6 \times U_{114}]_{\text{ext}}$	202	105	37
17	$[A_4 \times A_2 \times U_{570}]_{\text{ext}}$	198	133	41
19	$E_6 \times U_{14}$	228	119	42
20	$[A_6 \times U_{308}]_{\text{ext}}$	243	143	42
23	$[D_6 \times U_{50}]_{\text{ext}}$	300	161	41
26	$A_6 \times U_8$	349	199	39
30	$[A_6 \times U_{448}]_{\text{ext}}$	417	235	46
41	$[E_6 \times U_{258}]_{\text{ext}}$	610	297	44
41	$[A_6 \times U_{602}]_{\text{ext}}$	606	325	48
42	$[A_6 \times U_{616}]_{\text{ext}}$	627	337	46
44	$[A_6 \times U_{644}]_{\text{ext}}$	673	361	42
44	$[A_4 \times A_2 \times U_{1380}]_{\text{ext}}$	659	465	56
47	$[E_6 \times U_{294}]_{\text{ext}}$	728	367	46
54	$A_6 \times U_{16}$	857	455	51
58	$A_4 \times A_2 \times U_8$	923	611	56
86	$[A_6 \times U_{1232}]_{\text{ext}}$	1501	741	52
89	$[E_6 \times U_{546}]_{\text{ext}}$	1556	705	49
238	$A_4 \times A_2 \times U_{32}$	4959	2729	73
1,1	$A_2 \times A_1 \times A_2 \times A_1$	16	1	14

B-L Lifting



B-L Lifting



B-L Lifting

In this case all solutions can be enumerated.
There are two:

- Embedding of the Standard Model in the “wrong” E_8.
- Embedding of the Standard Model in *SO(32)*.

Chiral spectra are possible because these are stringy embeddings, not group theory embeddings. This is also the reason why embedding of the Standard Model in SO(10) does not necessarily yield standard families (see also E. Witten, 1985).

This replaces B-L by a non-abelian group.
Examples exist where no SM particles couple to it.
We lose B-L as a potential origin for R-parity.

$$\left[\mathrm{SM}\ , Q=\frac{1}{2}\right] \quad \times SU(5)\times SO(10)$$

Matter

$$3\times(Q,1,1)+3\times(U^c,1,1)+5\times(D^c,1,1)+2\times(D,1,1)$$
$$+5\times(L,1,1)+2\times(L^c,1,1)+3\times(E^c,1,1)$$

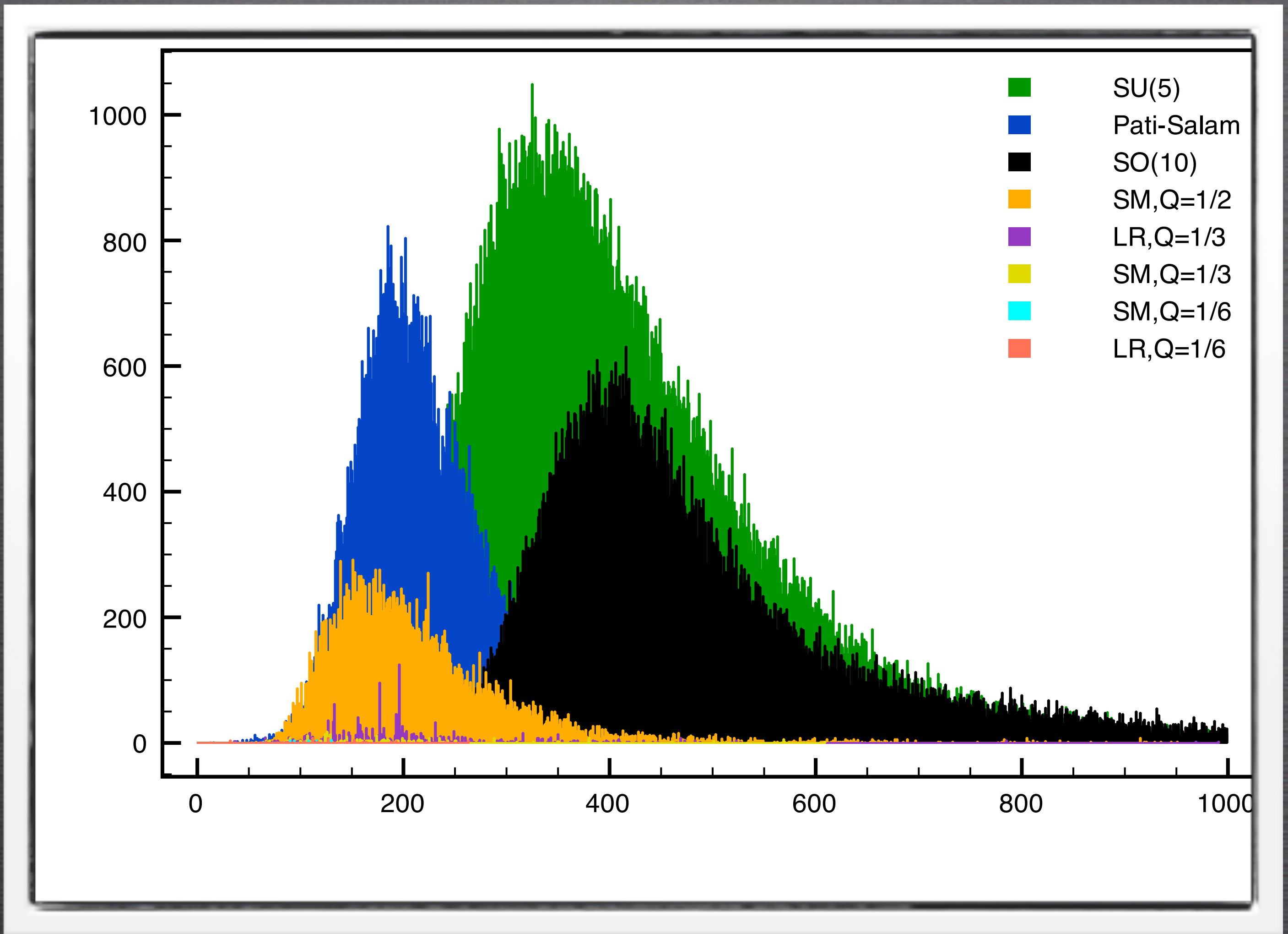
Singlets

$$24\times(N,1,1)+6\times(N,5,1)+7\times(N,\bar{5},1)+(N,10,1)+5\times(N,1,10)+(N,1,\overline{16})$$

Exotics

$$\left[2\times(1,1,-\tfrac{1}{2},5,1)+3\times(1,1,\tfrac{1}{2},5,1)+15\times(1,1,\tfrac{1}{2},1,1)+2\times(3,0,\tfrac{1}{6},1,1)+\mathrm{c.c}\ \right])$$
$$+\ 4\times(1,2,0,1,1)$$

$$(1,1,\frac{1}{2},1,\overline{16})+(1,1,-\frac{1}{2},1,\overline{16})$$



1000
800
600
400
200
0
0
200
400
600
800
1000
SU(5)
Pati-Salam
SO(10)
SM,Q=1/2
LR,Q=1/3
SM,Q=1/3
SM,Q=1/6
LR,Q=1/6

Results

Summary (all constructions)

Type	Chiral Exotics	GUT	Non-chiral	$N > 0$ fam.	No frac.
Standard*	37.4%	32.7%	20.5 %	9.3%	0
Standard, perm.	29.7%	33.4 %	27.9 %	8.9%	0
Free fermionic	1.5%	2.9%	94.4%	1.1%	0.072%
Lifted	28.3%	18.7%	51.9%	1.1%	0.00051%
Lifted, perm.	26.8%	8.9%	62.7 %	1.6%	0.00078%
$(\text{B-L})^*_{\text{Type-A}}$	21.3%	28.0%	50.4 %	0.3%	0.00017%
$(\text{B-L})_{\text{Type-A}}$, perm.	22.8%	8.1 %	69.1 %	0.03%	0
$(\text{B-L})^*_{\text{Type-B}}$	38.5%	8.7%	52.1%	0.6%	0
$(\text{B-L})_{\text{Type-B}}$, perm.	27.6%	7.3 %	65.0 %	0.1%	0

Vector-like Exotics

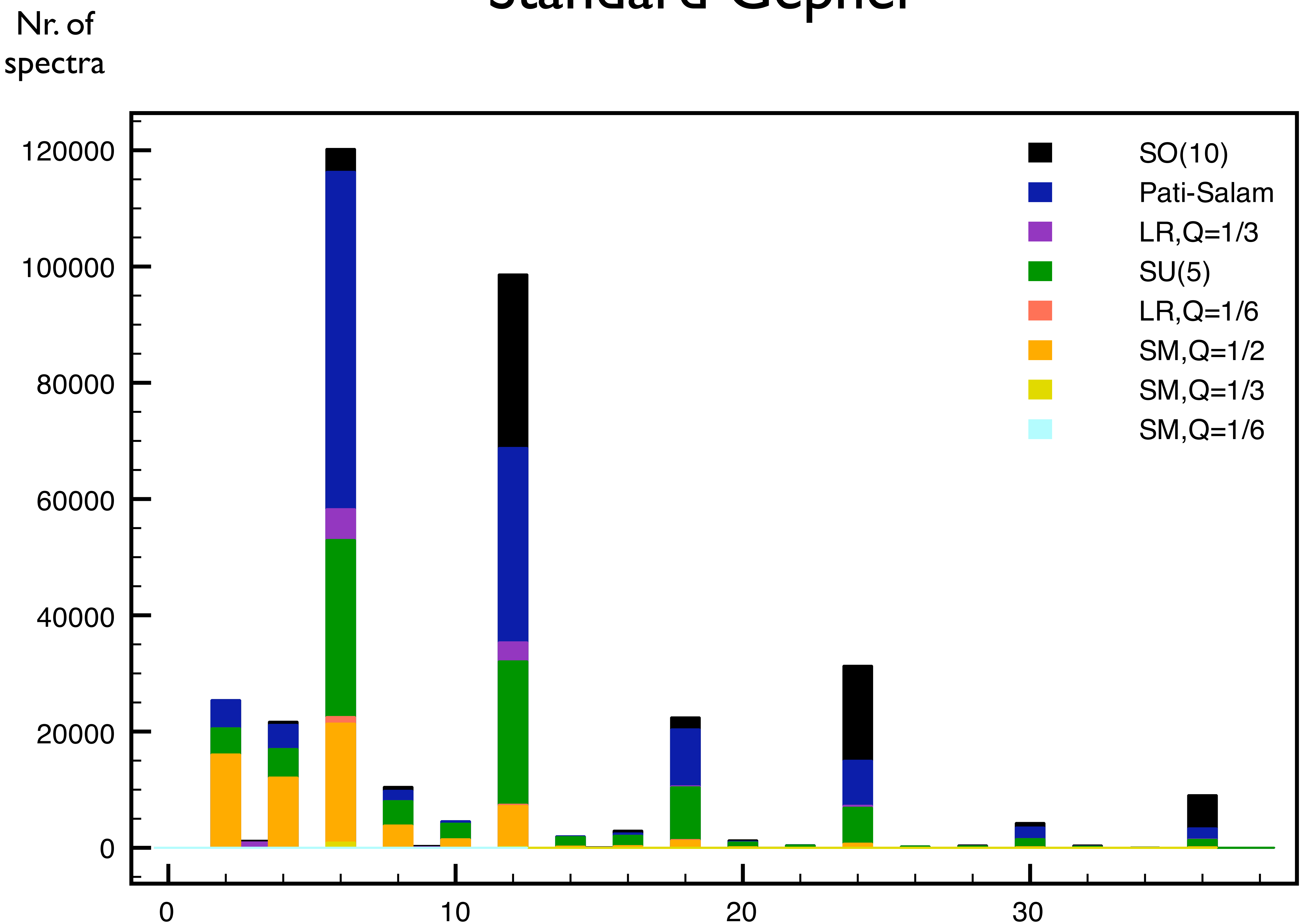
No Exotics

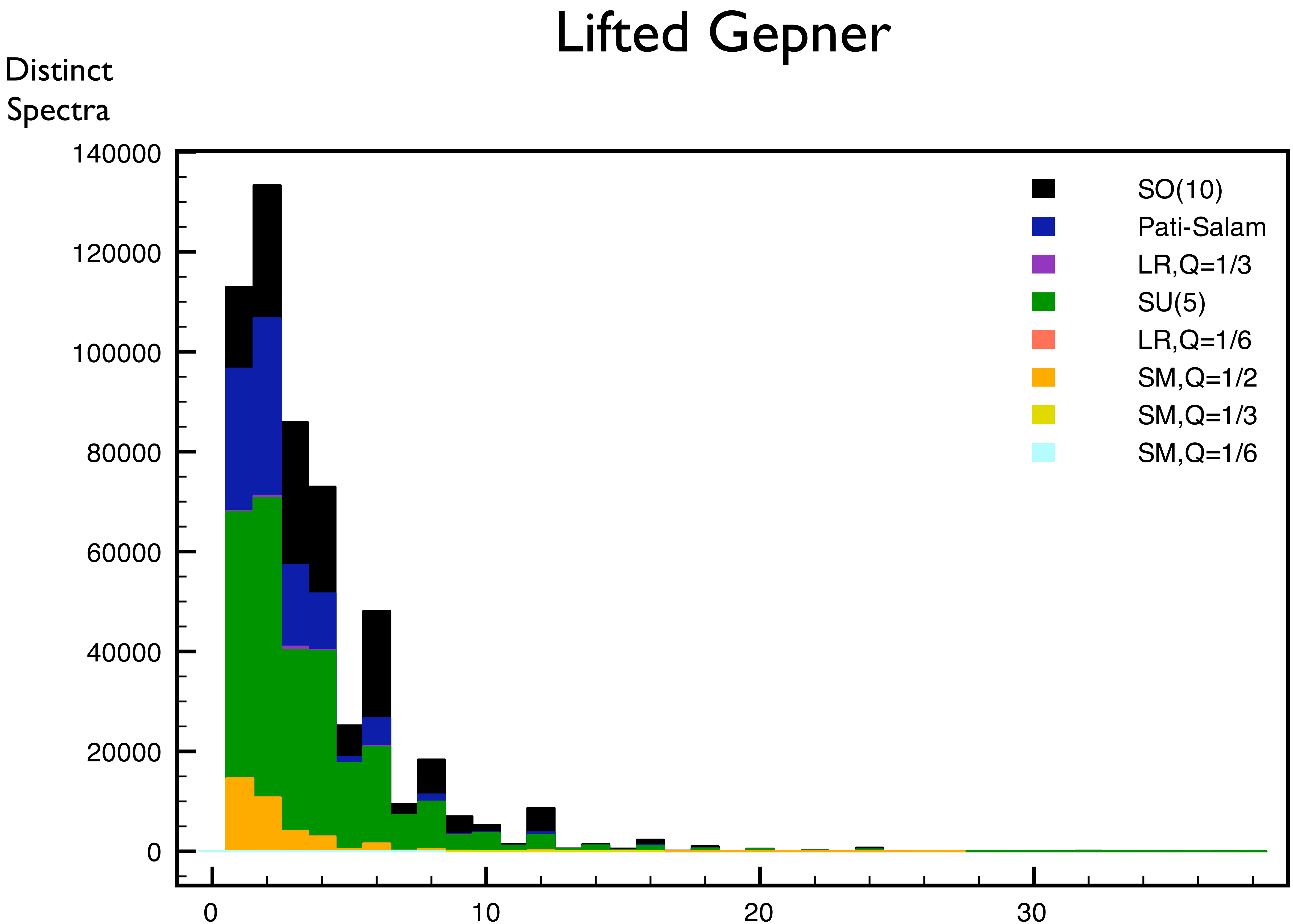
No-exotics models have an even number of families
For three-family examples see

Assel, Christodoulides, Faraggi, Kounnas and Rizos (2010) *[Free fermions]*

Blaszczyk, Nibbelink, Ratz, Ruehle, Trapletti, Vaudrevange (2010) *[Freely acting symmetries]*

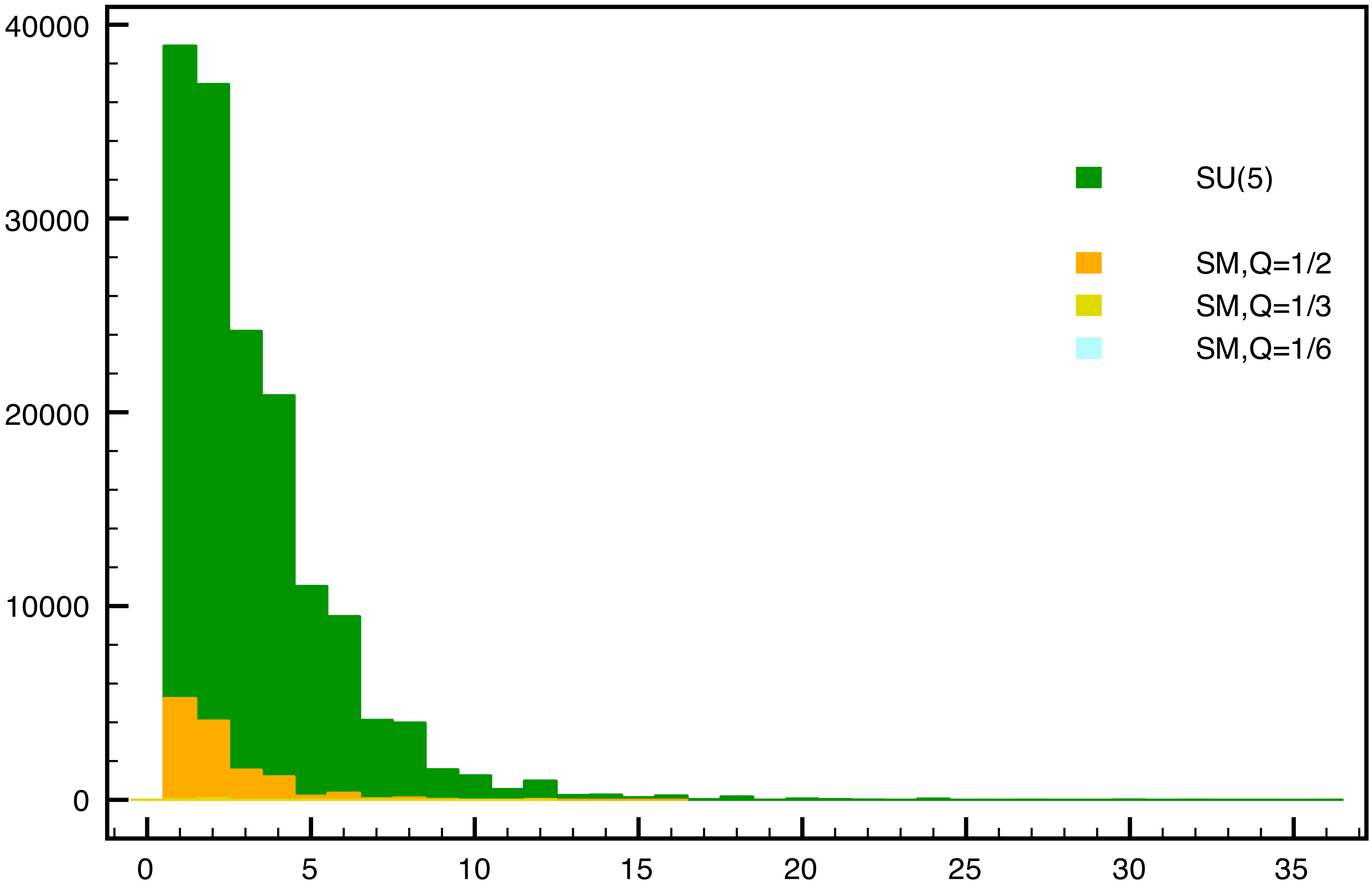
Standard Gepner



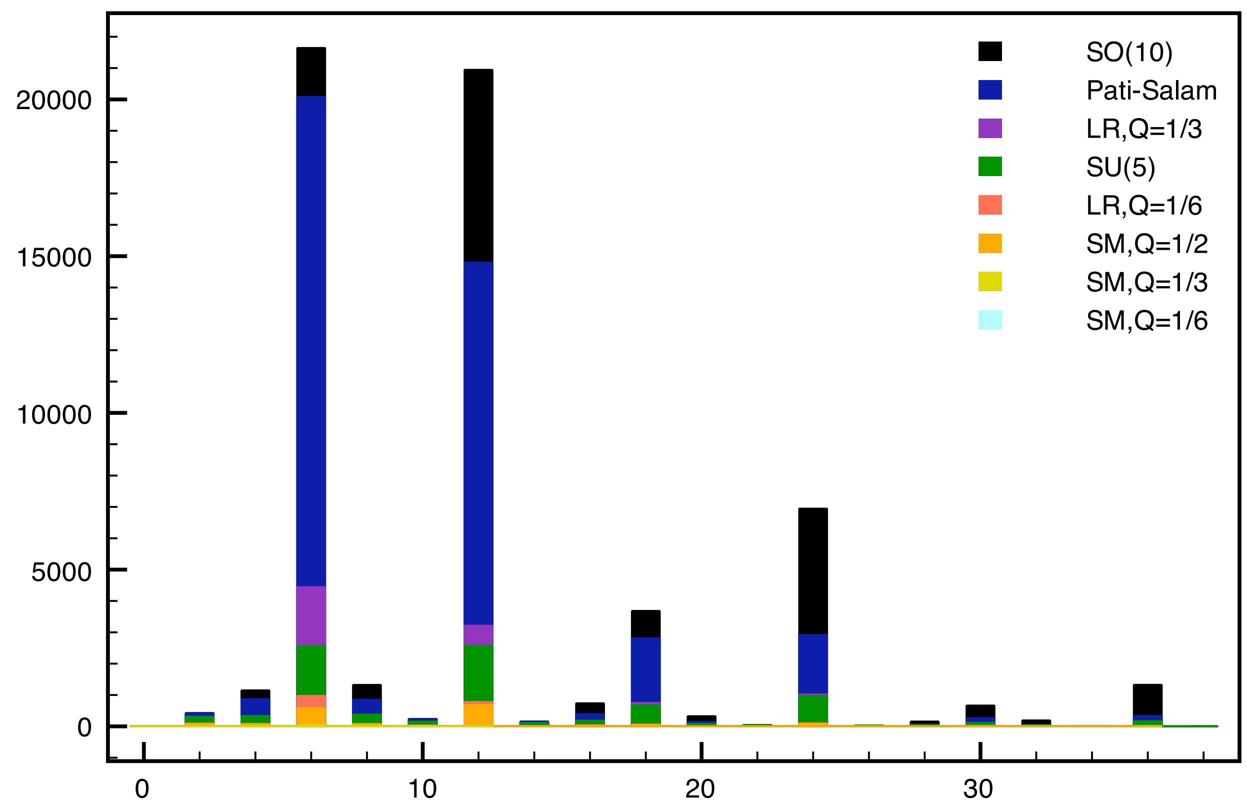


Lifted Gepner
Distinct
Spectra
140000
120000
100000
80000
60000
40000
20000
0
0
10
20
30
SO(10)
Pati-Salam
LR,Q=1/3
SU(5)
LR,Q=1/6
SM,Q=1/2
SM,Q=1/3
SM,Q=1/6

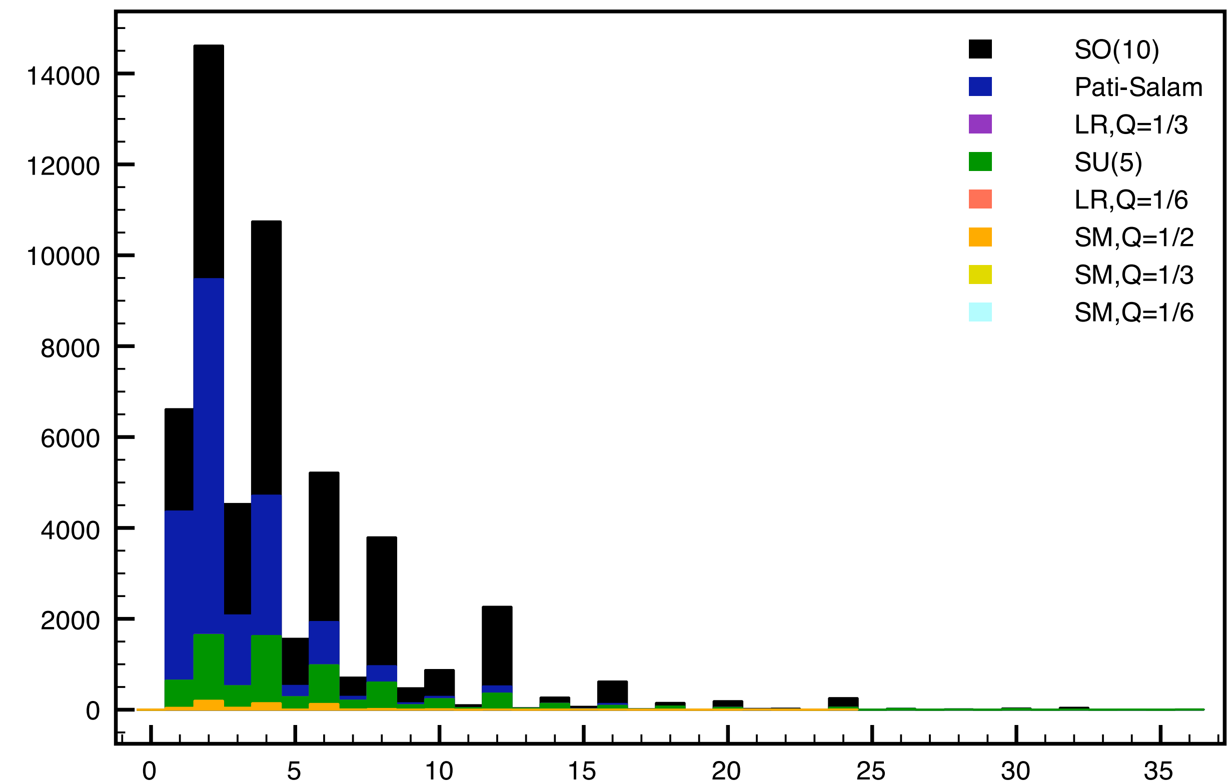
B-L Lifted Gepner (lift A)



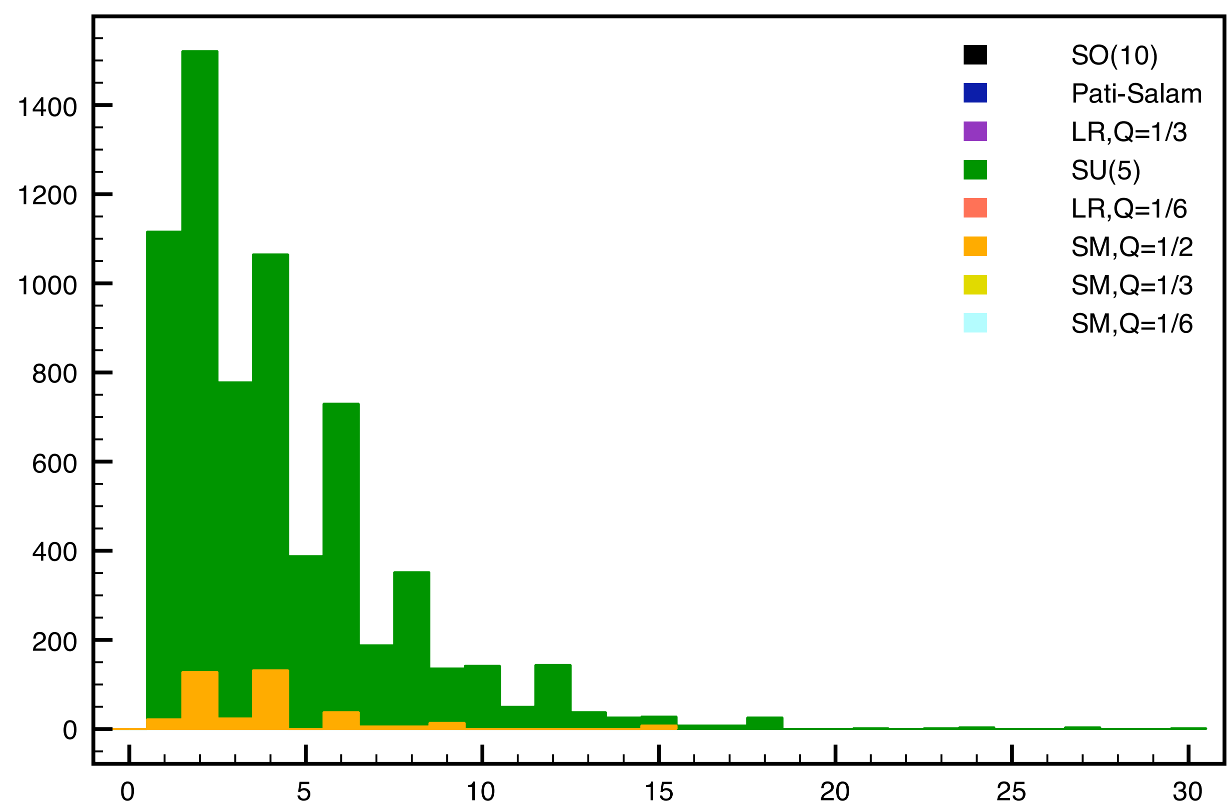
Permutation orbifolds *(with Michele Maio)*



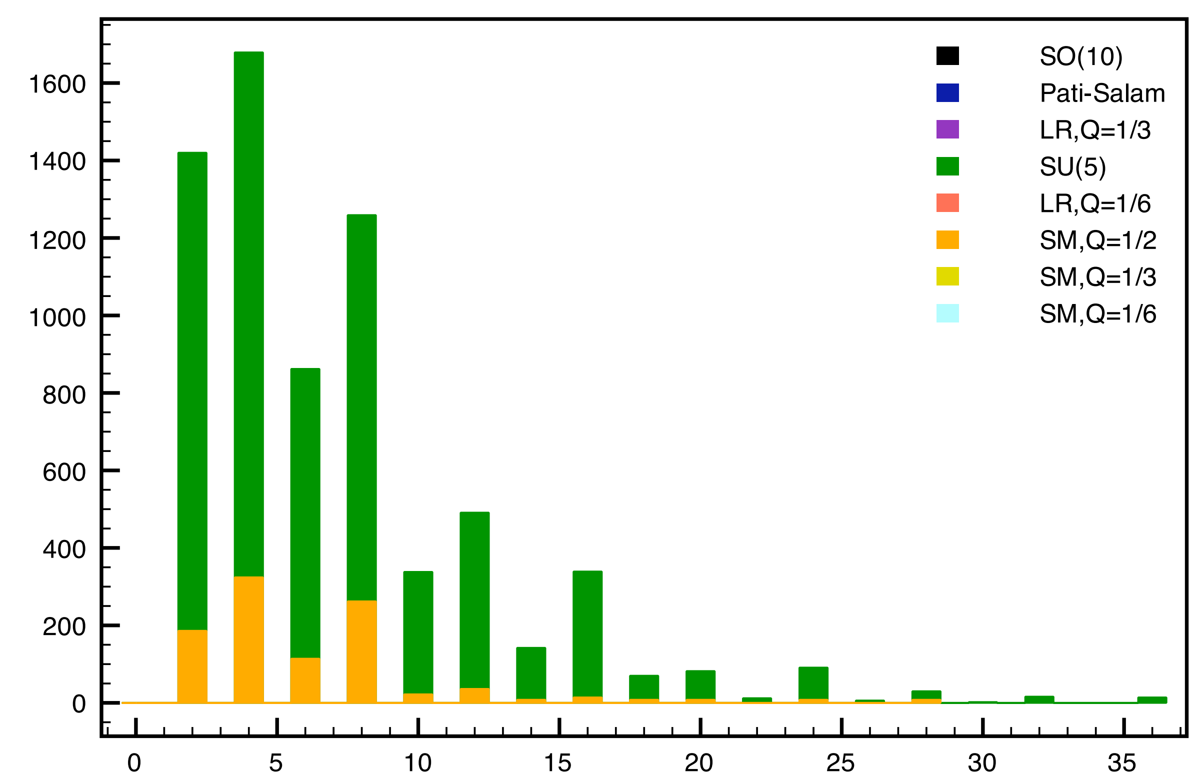
Standard



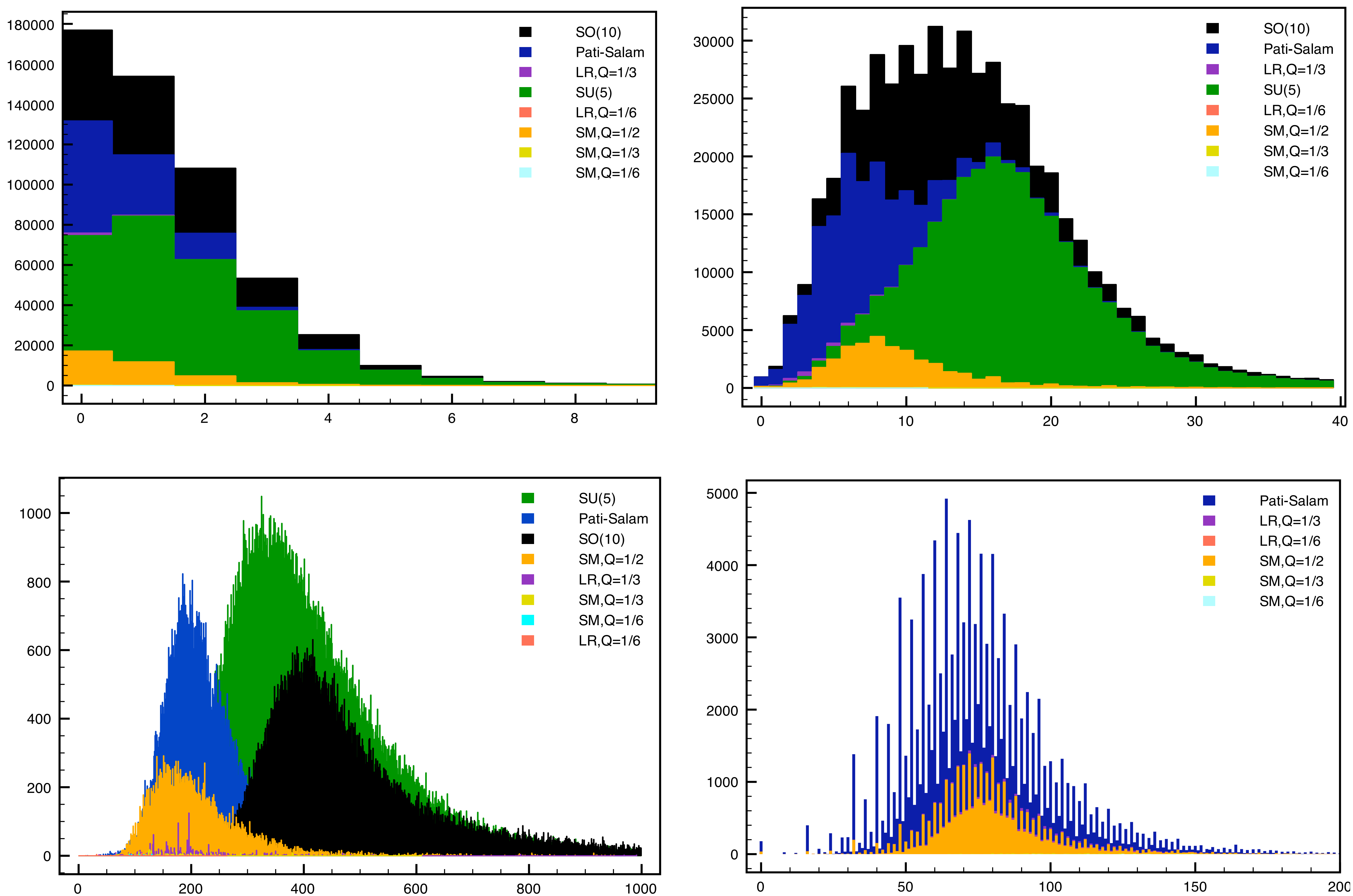
Lifted



B-L lift A



B-L lift B



180000
160000
140000
120000
100000
80000
60000
40000
20000
0
0
2
4
6
8
SO(10)
Pati-Salam
LR,Q=1/3
SU(5)
LR,Q=1/6
SM,Q=1/2
SM,Q=1/3
SM,Q=1/6
30000
25000
20000
15000
10000
5000
0
0
10
20
30
40
SO(10)
Pati-Salam
LR,Q=1/3
SU(5)
LR,Q=1/6
SM,Q=1/2
SM,Q=1/3
SM,Q=1/6
1000
800
600
400
200
0
0
200
400
600
800
1000
SU(5)
Pati-Salam
SO(10)
SM,Q=1/2
LR,Q=1/3
SM,Q=1/3
SM,Q=1/6
LR,Q=1/6
5000
4000
3000
2000
1000
0
0
50
100
150
200
Pati-Salam
LR,Q=1/3
LR,Q=1/6
SM,Q=1/2
SM,Q=1/3
SM,Q=1/6

	Does $SU(3) \times SU(2) \times U(1)$ imply family structure?	Do chiral families imply absence of (light) fractional charges?	N_{family}?
Field Theory	No restrictions apart from anomaly cancellation	Yes, assuming $SU(5)$ or $S(U(3) \times U(2))$	No restrictions
Heterotic Strings ("Classic")	Correct restriction to small reps, but chiral exotics likely.	No. (but rare cases exist)	Strongly peaked at small values. Three not strongly suppressed
Orientifolds	?	Yes, for three or four branes.	Very strongly peaked at small values. Apparent dip at three.