History And Perspectives

Let B be a smooth weak Fano toric threefold induced by a crepant resolution of a Fano toric threefold corresponding to a 3d reflexive polytope Δ° via an FRST.

We thank N. Hitchin for explaining to us the properties of Fano three-folds, and R. Schrock for discussions.

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DO QUARKS KNOW ABOUT KÄHLER METRICS?

K. PILCH [1] and A.N. SCHELLEKENS [2]

Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, Long Island, NY 11794, USA

Received 1 July 1985

We study compactification of ten-dimensional E_8 $(\times E_8)$ super-Yang–Mills theory on the coset manifold $SU(3)/U(1)^2$. We obtain a three generation SO(10) model without mirror fermions. The internal space admits both Kähler and non-Kähler metrics, but the correct fermion mass spectrum can be obtained only if the metric is Kähler.

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$$m_u = 2.3\ \text{MeV}\,,\quad m_c = 1.0\ \text{GeV}\,,\quad m_t = 39.5\ \text{GeV}\,,\quad m_d = 9.4\ \text{MeV}\,,$$

$$m_s = 219\ \text{MeV}\,,\quad m_b = 5.2\ \text{GeV}\,,\quad m_W = 84.1\ \text{GeV}\,.$$

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CHIRAL FOUR-DIMENSIONAL HETEROTIC STRINGS FROM SELF-DUAL LATTICES

W. LERCHE

CERN, Geneva, Switzerland

D. LÜST

Max-Planck-Institut für Physik und Astrophysik, Föhringer Ring 6, 8000 München 40, FRG

A.N. SCHELLEKENS

CERN, Geneva, Switzerland

Received 24 November 1986

It is shown how our previous work on lattice constructions of ten-dimensional heterotic strings can be applied to four dimensions. The construction is based on an extension of Narain's lattices by including the bosonized world-sheet fermions and ghosts, and uses conformal field theory as its starting point. A natural embedding of all these theories in the bosonic string is automatically provided. Large numbers of chiral string theories with and without $N = 1$ supersymmetry can be constructed. Many features of their spectra have a simple interpretation in terms of properties of even self-dual lattices. In particular we find an intriguing relation between extended supersymmetry and exceptional groups.

In four dimensions things are far more complicated. In the worst possible case we have a lattice $\Gamma_{22;14} = (\Gamma_{22})_L \times (D_5 \times (D_1)^9)_R$, which can be mapped to $(\Gamma_{22} \times D_3 \times (D_7)^9)_L$, a euclidean lattice of dimension 88. A lower limit on the total number of such lattices is provided by the Siegel mass formula [21] [22]

$$\sum_{\Lambda} g(\Lambda)^{-1} = (8k)^{-1} B_{4k} \prod_{j=1}^{4k-1} (4j)^{-1} B_{2j}, \tag{5.1}$$

where the sum is over all even self-dual lattices of dimension $8k$, and $g(\Lambda)$ is the order of the automorphism group of Λ. Because $g(\Lambda) \geqslant 1$ the right hand side is a lower limit of the number of lattices (B_{2j} are the Bernoulli numbers). For $k = 11$ this number is of order 10^{1500}! The requirement that Λ should contain $D_3 \times (D_7)^9$ with a triplet constraint will reduce the number considerably, but clearly this is not a viable approach towards classification. It only tells us that the number of chiral theories is finite, but most likely extremely large*.

* A more reasonable but less rigorous estimate can be made by observing that the 88-dimensional lattice has (at most) 32 factors, so that combinatorically their classification should be similar to the classification of even self-dual lattices of dimension 32 with D_1 lattices as building blocks. On the basis of such an estimate one would still expect a very large number of solutions.

This was not a pointless exercise:
It was the only way to demonstrate that the total number of solutions was finite.

This is obvious for free-fermionic constructions.

It was not even obvious that the set of solutions was discrete:
Narain compactifications belong to the same class, and had Narain moduli.

But we understood that the Narain moduli were fixed by the requirement of $N < 2$ space-time supersymmetry, which fixed the rightmover lattice.

This led to the misconception that there were no moduli at all; in fact they were not even discussed in the paper.

But there were other scalars, which do give rise to moduli.

schemes in which they appear. In Calabi–Yau compactifications the moduli are unavoidable, since one can always change the overall scale of the metric. In contrast, here any change in the radius of the free bosons in (2.12) would break the $N = 1$ sub–algebra, and is thus forbidden by the $N = 1$ conformal gauge condition. Thus, the compactifications described here are inherently free of the moduli problem. Unfortunately, there are tachyons in the theory (22), but presumably these can be eliminated. We believe that further study of these theories will enable the constructions of models which are free of moduli and have a fully realistic spectrum.

ACKNOWLEDGEMENTS

I wish to thank J. Harvey, V. Kaplunovski, and E. Witten for helpful comments. I am particularly grateful to S. Shenker for a crucial discussion.

288280574204696340659995365355361558420650869220808535389844395511991338190005587609470524745658514346741209677967663558951577295279008725702279578858099556070642887164428345636181703539362916493828664832262798280879533906856341368554779410767322917610720983055163706476135037818392025217235782950745217191830223209495429766903985820510780966889267834337175858276142160745242015826356829483560681248200858959990674335933942905918281521769790287262990709457379764792913635359138351362493098578497575381436329442145995280031770656323805559499189436018271763077144823089799090573474453384288020033959243770070092574247932583489907794066646937140055364569423858604635037218917200432131436957638870102597239829134337988638890436715564645907806576250529048337296031946159664539308058934641787425405406480737417294441892751775118523427456157975096479184243428355881302764065549143448157244744678697675901739379699752662922037818713124994059166633172192672544495952828337015412861970807544203267583108253592981378133468568237870250484151531524511148614048647141067291444604667010597679753470530498270194821752736

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444512851999576745742614885825556899563085867574239177979318557353620346007638233366830819482690967320840731821025651461985853730746593601898151936000000000000000000000000000

Even self-dual lattice of dimension 8k

Dimension	Lower limit	Upper limit	Actual Number
8	$2.870554085831864 \times 10^{-9}$	1	1
16	$4.977181647677474 \times 10^{-18}$	2.4160839160839161	2
24	$1.587356093933540 \times 10^{-14}$	$4.130854882089717 \times 10^{16}$	24
32	$8.061846587120415 \times 10^{7}$	$2.277750478211998 \times 10^{52}$	?
40	$8.786162893954708 \times 10^{51}$	$1.970535004851803 \times 10^{111}$	?
48	$3.051507011767375 \times 10^{121}$	$2.665648986868395 \times 10^{196}$	?
56	$1.276238439666753 \times 10^{219}$	$1.634633237068218 \times 10^{310}$	?
64	$9.544539505706936 \times 10^{346}$	$5.585108422305436 \times 10^{454}$	?
72	$9.613130349683812 \times 10^{506}$	$6.949609601107582 \times 10^{631}$	?
80	$5.862018298127880 \times 10^{700}$	$1.267986279010439 \times 10^{843}$	?
88	$6.485314719426174 \times 10^{929}$	$9.307090939221263 \times 10^{1089}$	?

Growth exceeds free (anti)-periodic fermionic construction of such theories.

Bug or Feature?

Perspectives ~1987

Conclusions of a talk in the Uppsala EPS Conference (July 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. All we can reasonably demand is that there exists a consistent and stable ground state which describes all physics correctly. The recent "ground state explosion" (which may well turn out to be just the tip of an iceberg), certainly enhances the chances that such a ground state does indeed exist, although pessimists will probably take a dimmer view of the recent developments.

CERN-TH-4807/87
Talk given in the parallel session on Superstrings and Supergravity. Conference: C87-06-25 (Uppsala EPS HEP 1987:0272)

Perspectives ~1987

(non-pc version)

- **String theory has a huge anthropic landscape**

  (ensemble)

- **Compactification is an outdated concept**
- **No need for Grand Unification**
- **Hierarchy problem must be reconsidered**
- **There is information in landscape distributions**
- **We need at least 10^{130} vacua for the CC**

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  Douglas (2004), String landscape
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Quantum Cosmology and the Constants of Nature
Alexander Vilenkin (1995)

"The number of different compactifications in superstring theories is believed to be $\gtrsim 10^4$"

Perspectives ~1987

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  Bousso, Polchinski (2000)

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  Douglas (2004), String landscape
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  Bousso, Polchinski (2000)

Sakharov, A., 1984, Zh. Eksp. Teor. Fiz. 87, 375 [Sov. Phys. JETP 60, 214 (1984)]

If the small value of the cosmological constant is determined by "anthropic selection," then it is due to the discrete parameters. Here Λ either is equal to exactly 0 in some version or is extremely small. In the latter case we should assume that the number of versions of the set of discrete parameter is large enough that the range of values of Λ in the vicinity of the point $\Lambda = 0$ is quite "dense."

This obviously requires a large value of the number of dimensions of the compactified space and/or the presence in some topological factors of a complex topological structure (such as a large number of "handles") for some topological cofactors.

Joseph Polchinski

Memories of a Theoretical Physicist, arXiv:1708.09093

I told our postdoc, Sean Carroll, that if the CC turned out to be there, he could have my office. It would mean that the anthropic principle was here, and I would have to give up physics. I make a lot of comments like this that I do not remember […] But Sean remembered, and as he introduced me at a meeting two years later, he asked when he was going to get the office.

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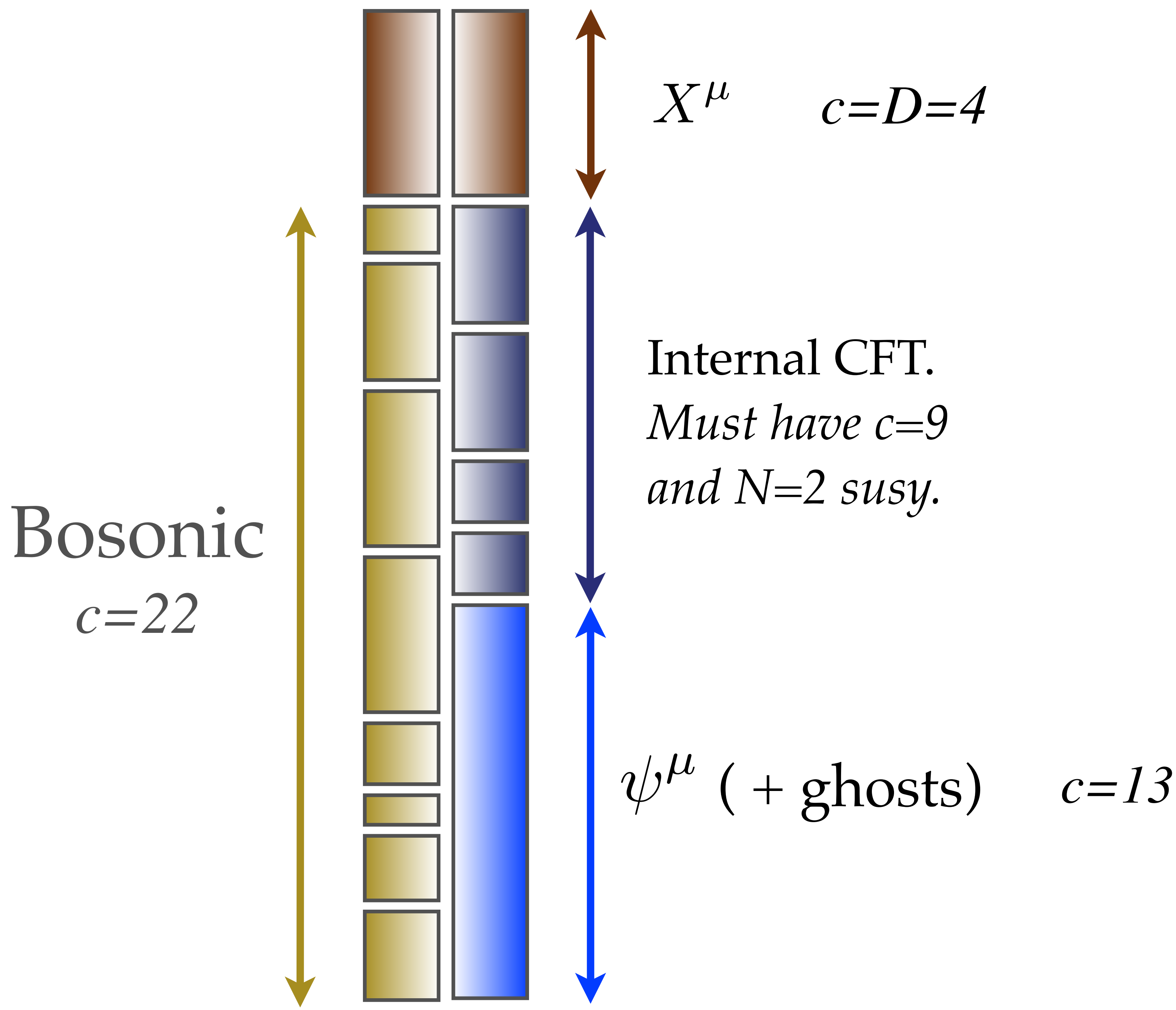
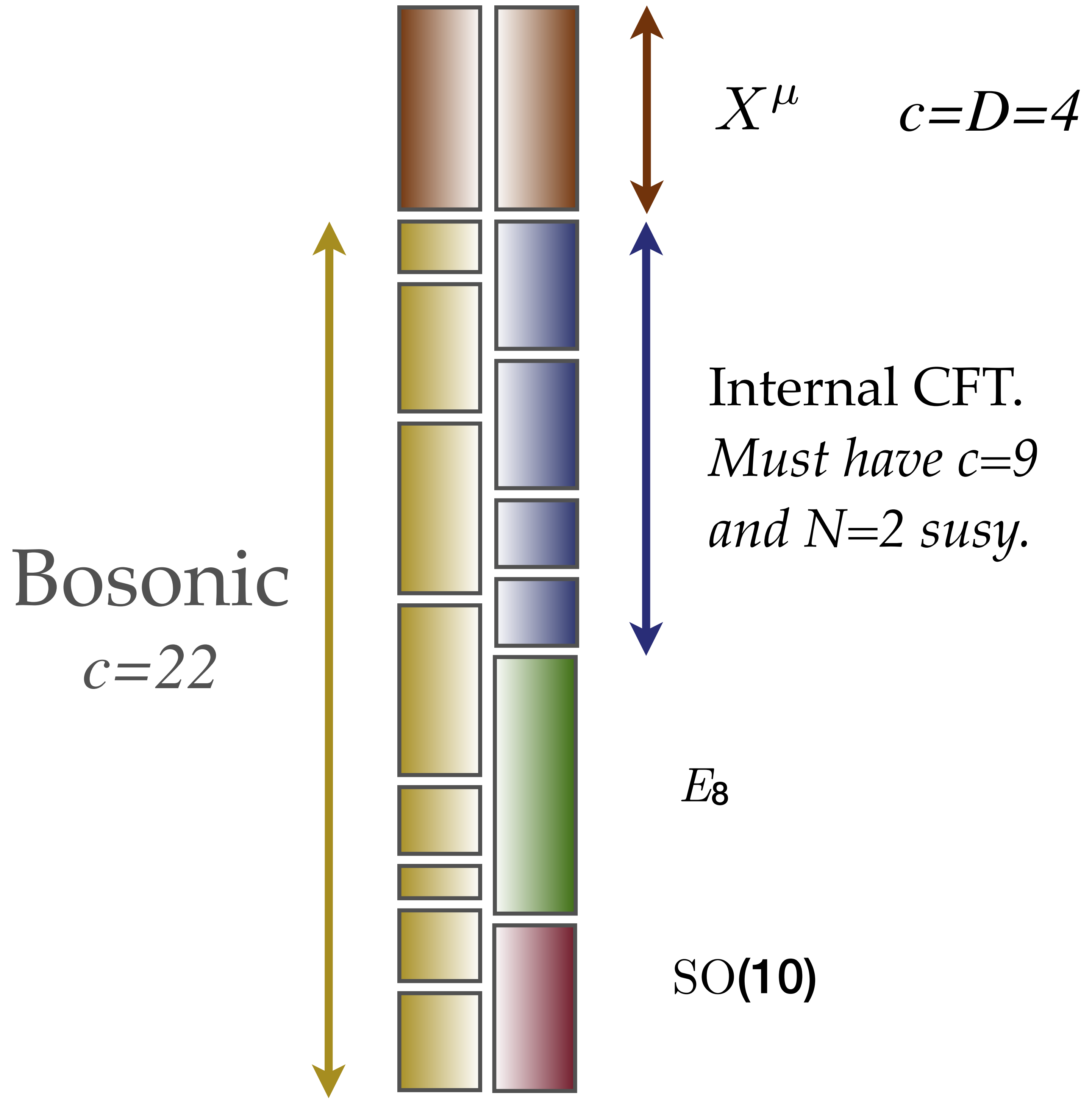
As far as I know, this is the first paper written about string theory and the anthropic principle, a real illustration of the power of anthropic denial.

Heterotic Strings

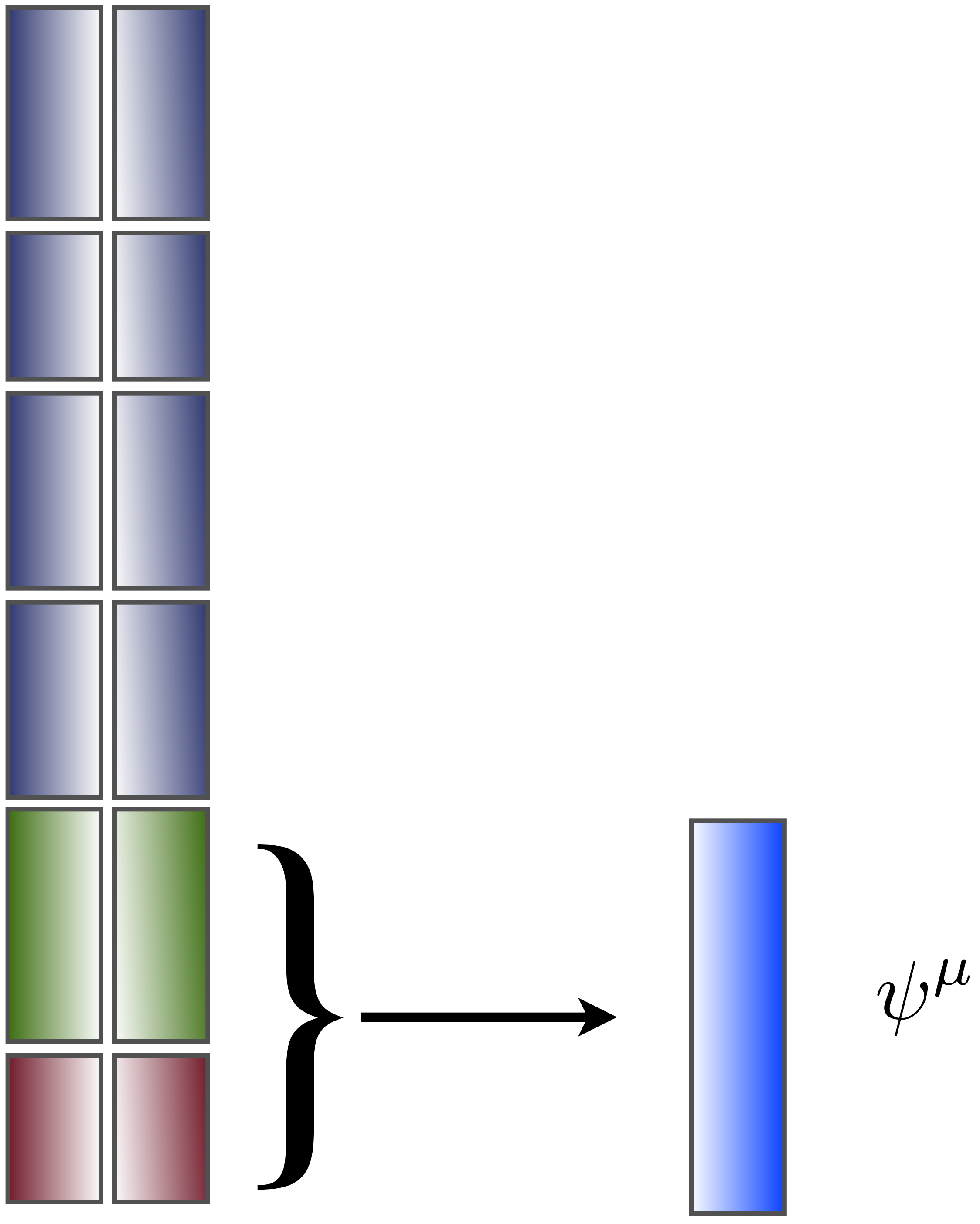
Heterotic strings in CFT



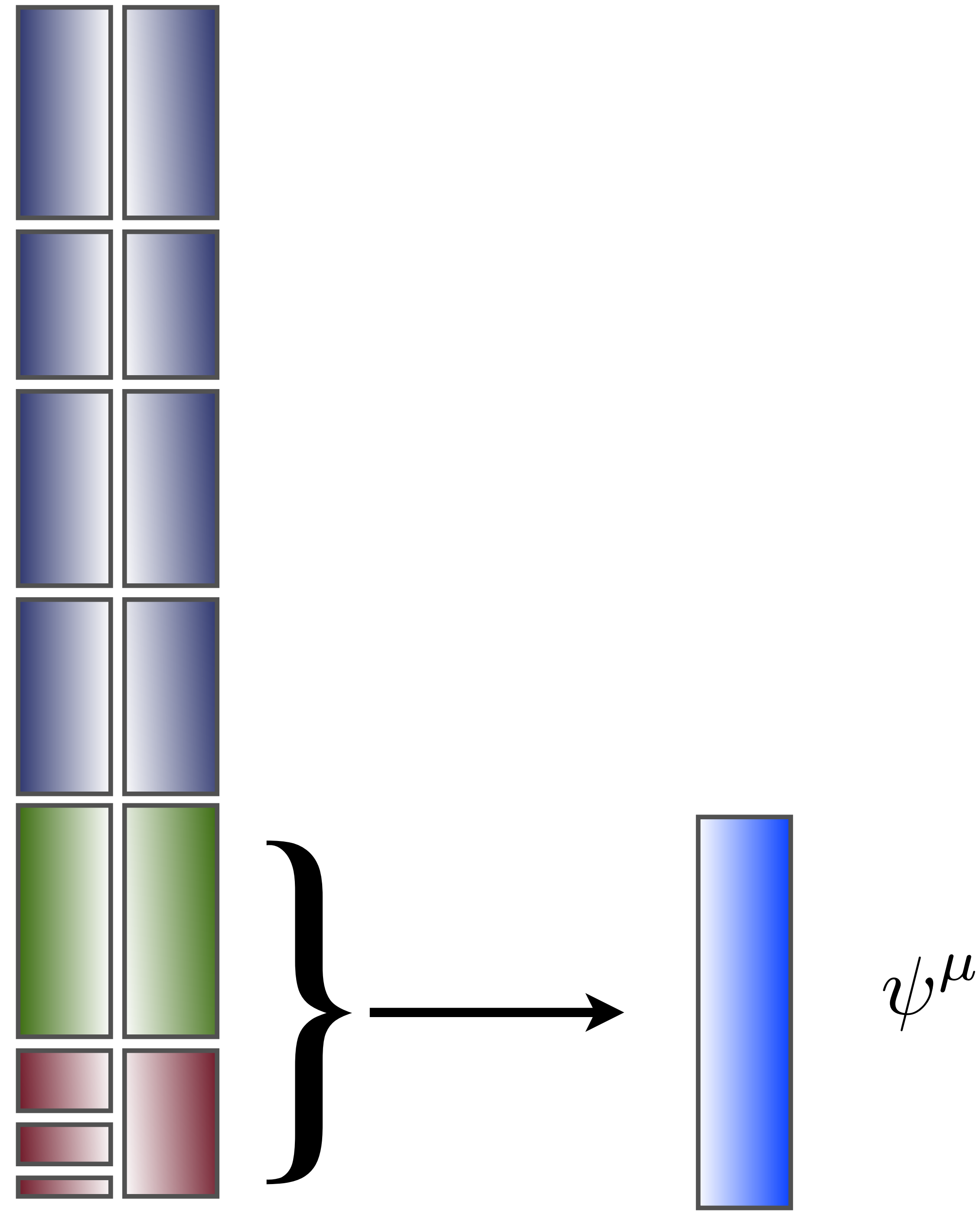
Heterotic strings in CFT



Gepner models:
Use symmetric MIPF



Gepner models:
Use symmetric MIPF

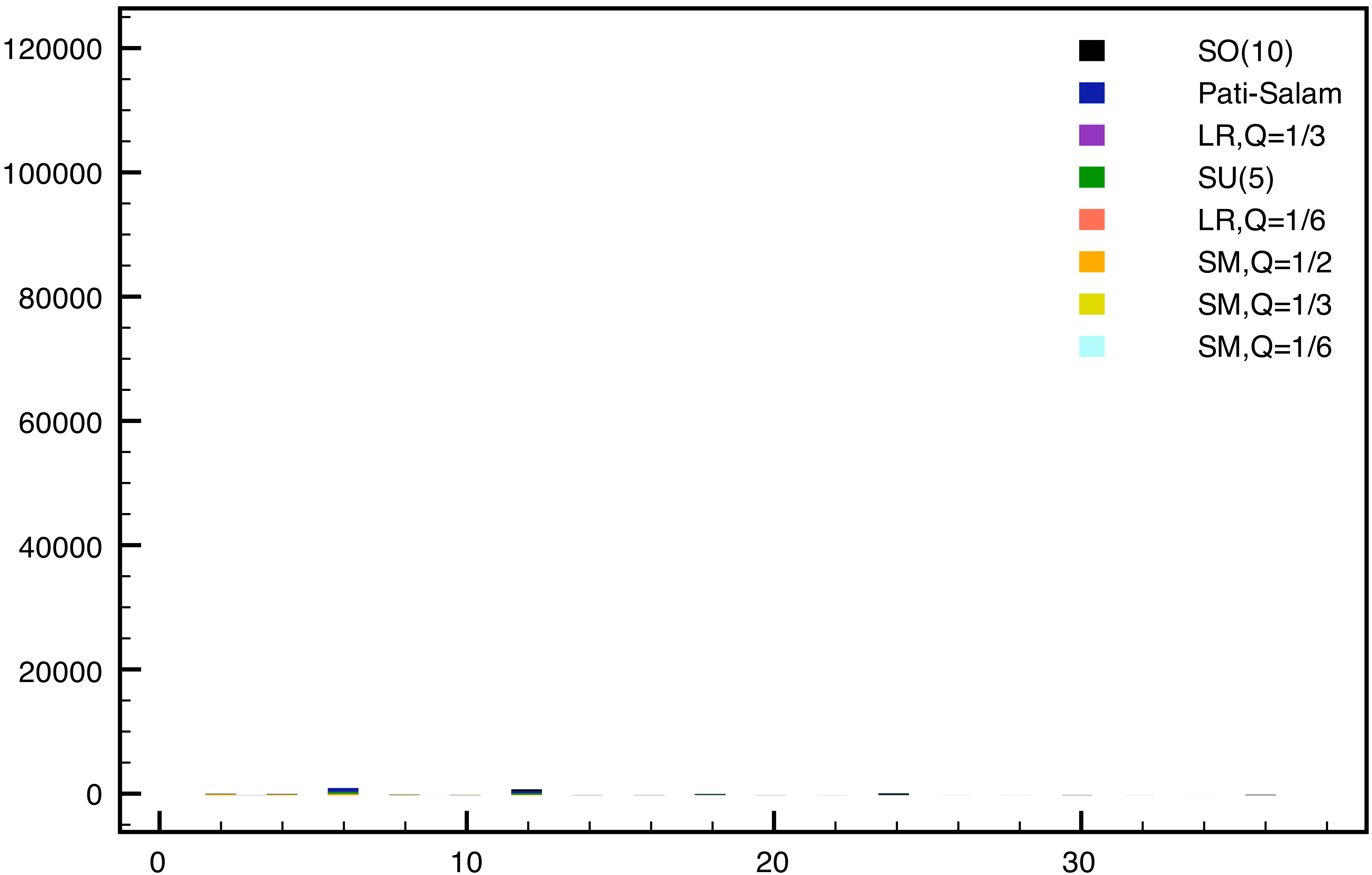


SO(10) currents replaced by
operators of higher weight

Gauge group $H \subset SO(10)$; families are (16)'s

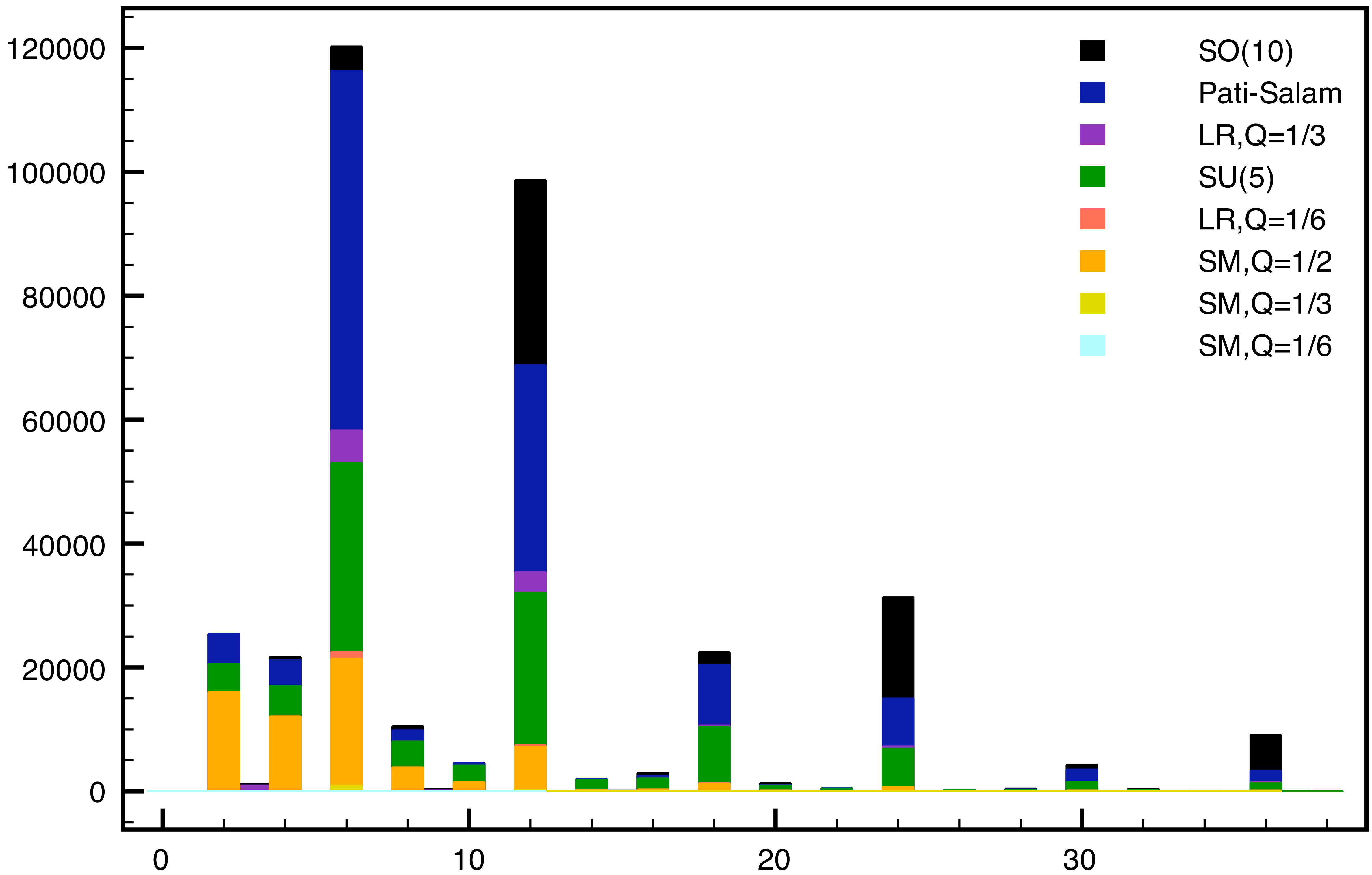
With S.Yankielowicz (1989)

Nucl.Phys. B330 (1990) 103-123

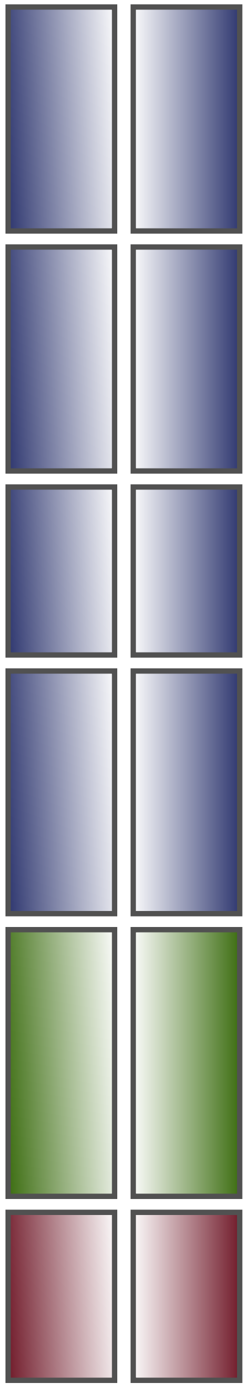


With B. Gato Rivera (2010)

Nucl.Phys. B841 (2010) 100-129

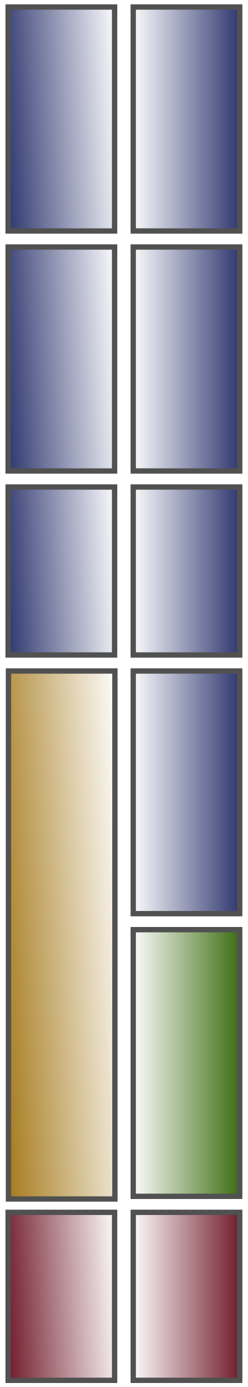


Heterotic Weight Lifting



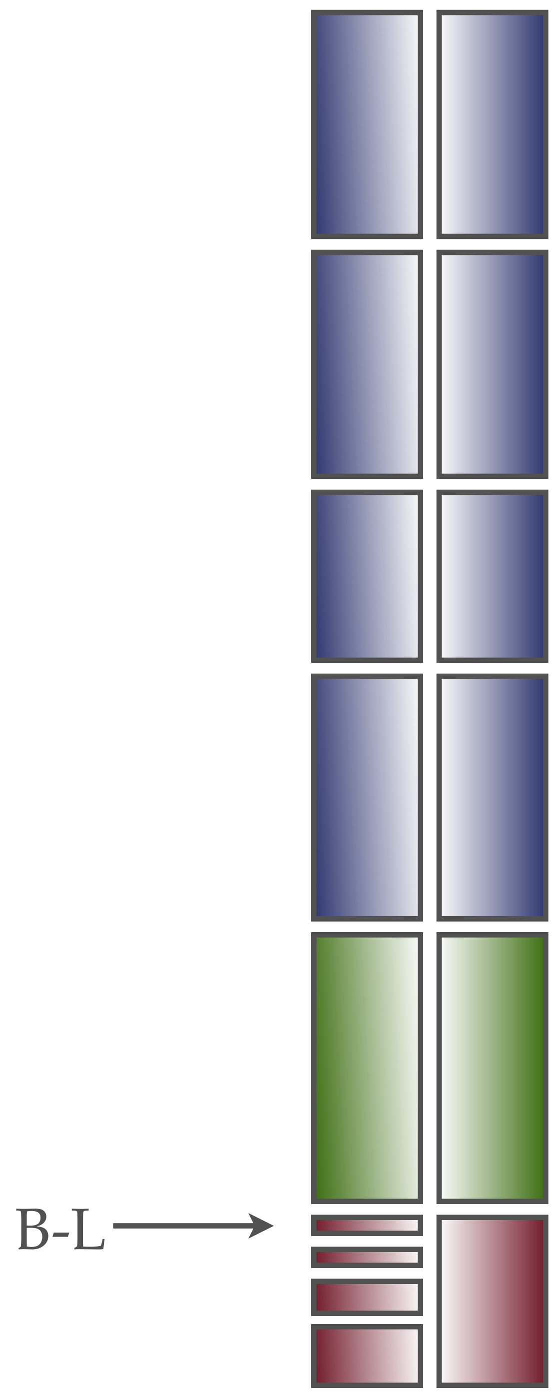
Gato-Rivera, Schellekens, 2009

Heterotic Weight Lifting

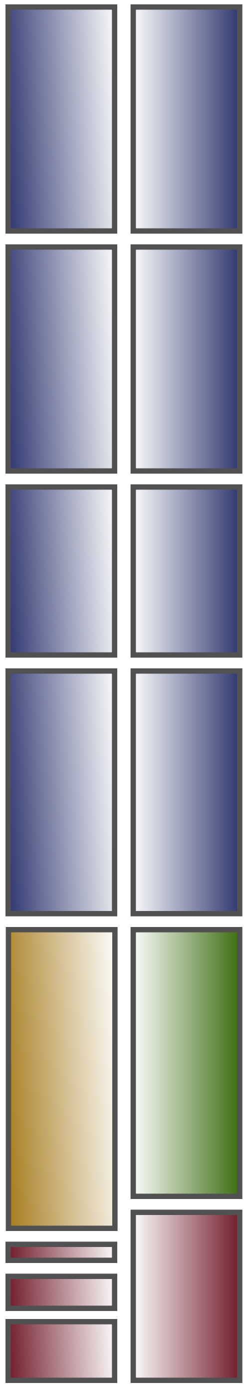


Gato-Rivera, Schellekens, 2009

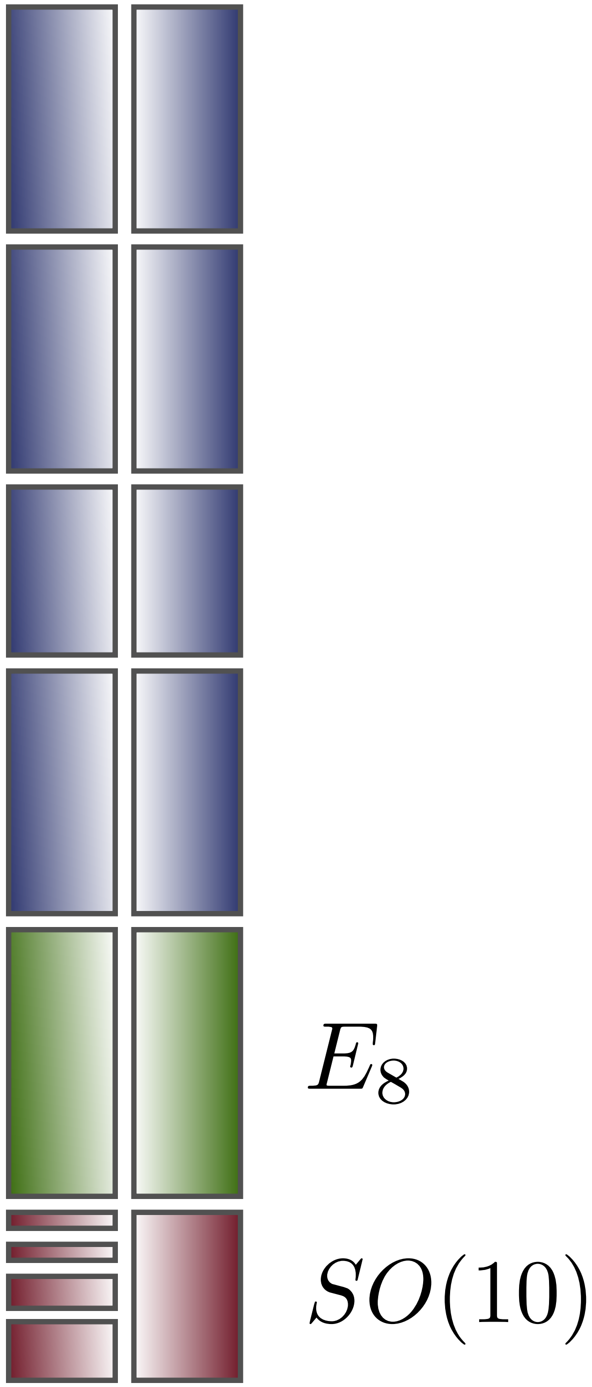
B-L Lifting



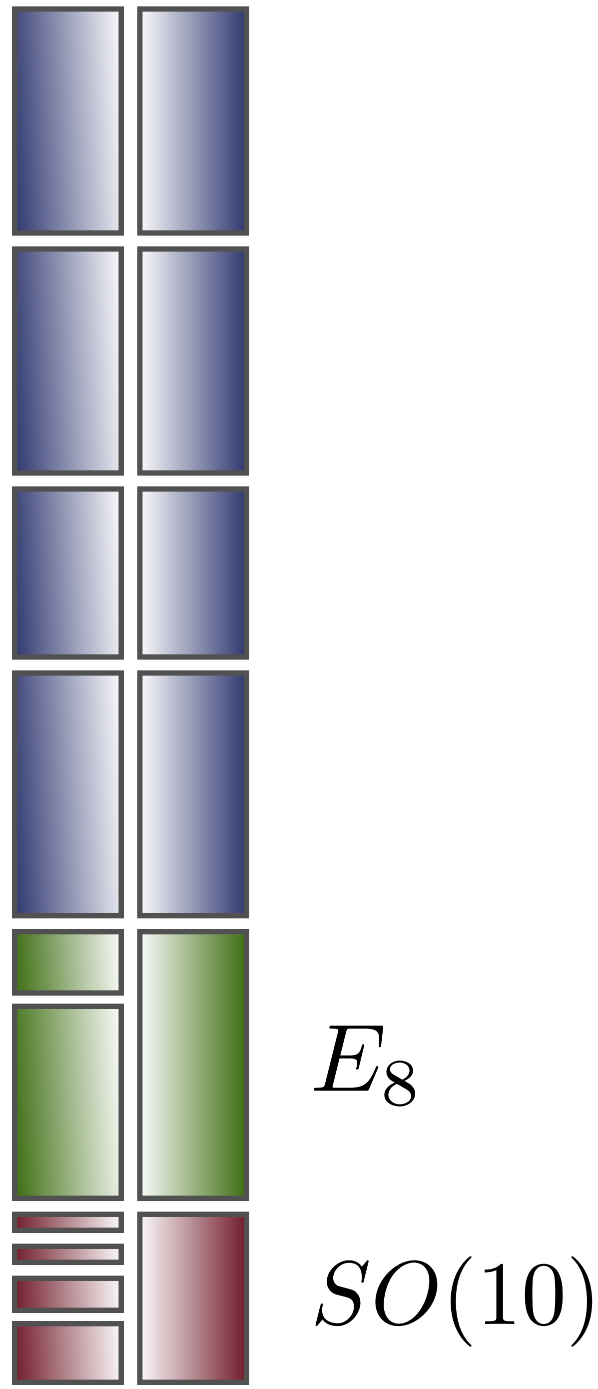
B-L Lifting

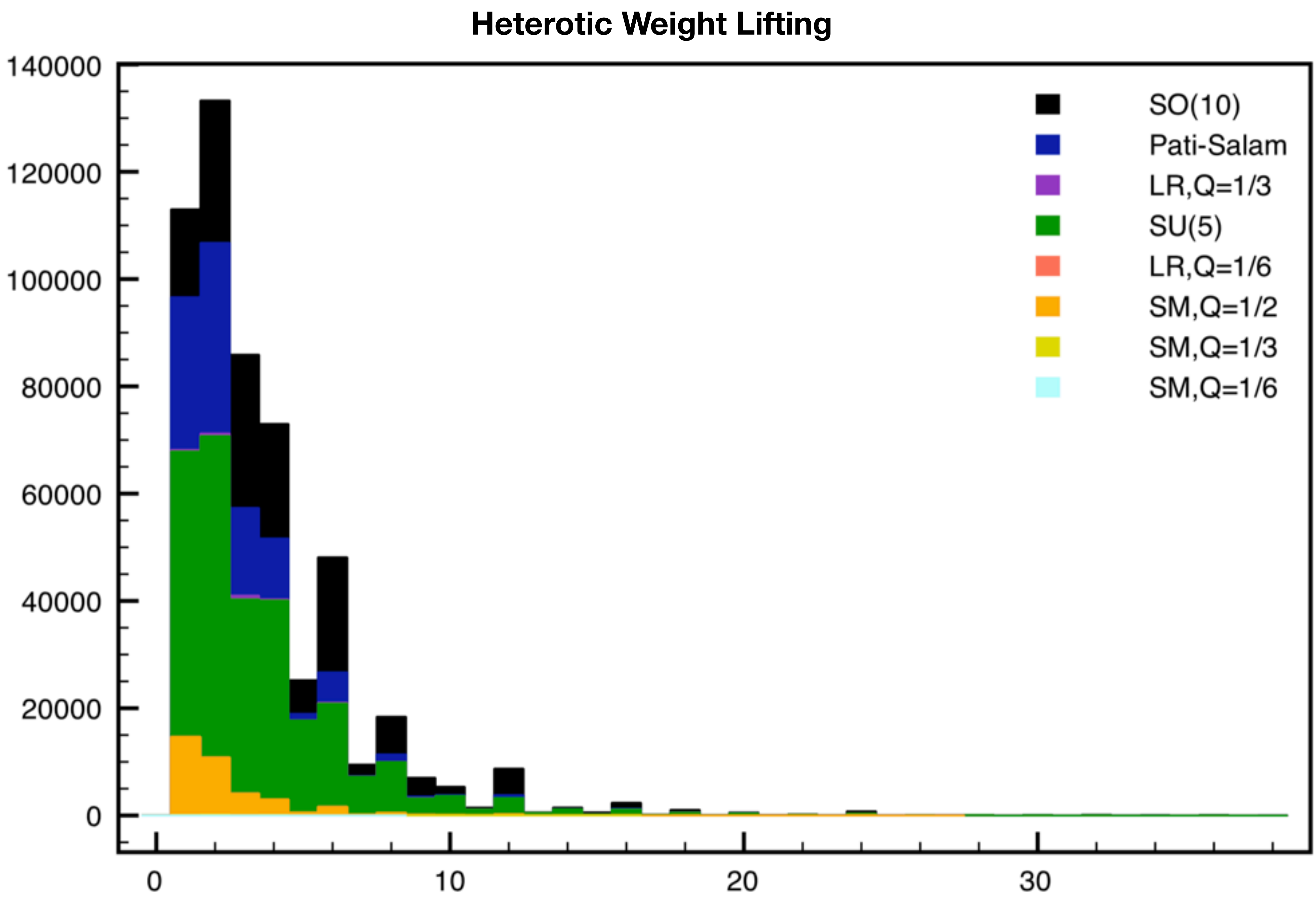


E_8 splitting



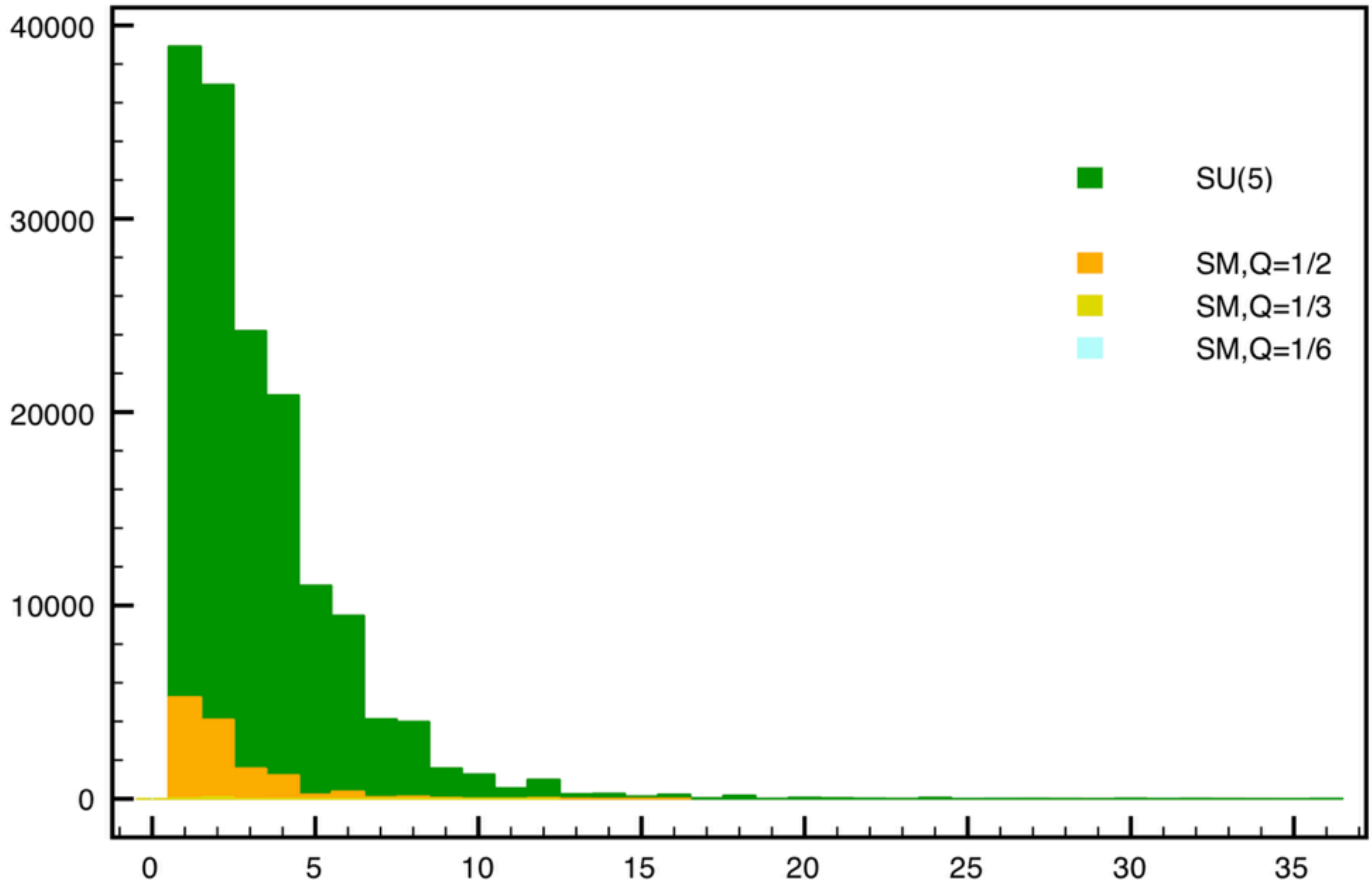
E_8 splitting



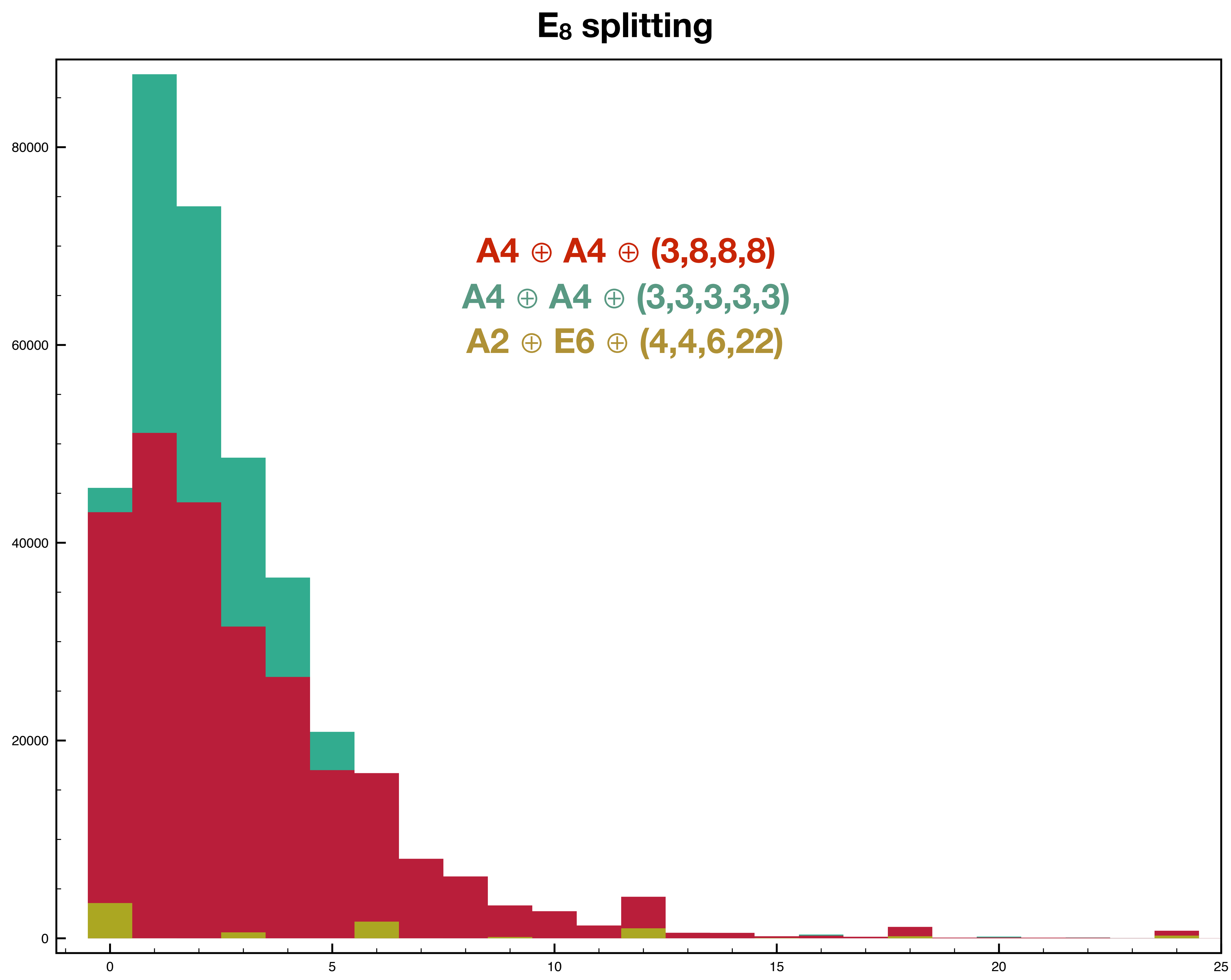


Heterotic Weight Lifting
140000
120000
100000
80000
60000
40000
20000
0
0
10
20
30
SO(10)
Pati-Salam
LR,Q=1/3
SU(5)
LR,Q=1/6
SM,Q=1/2
SM,Q=1/3
SM,Q=1/6

B-L Lifting

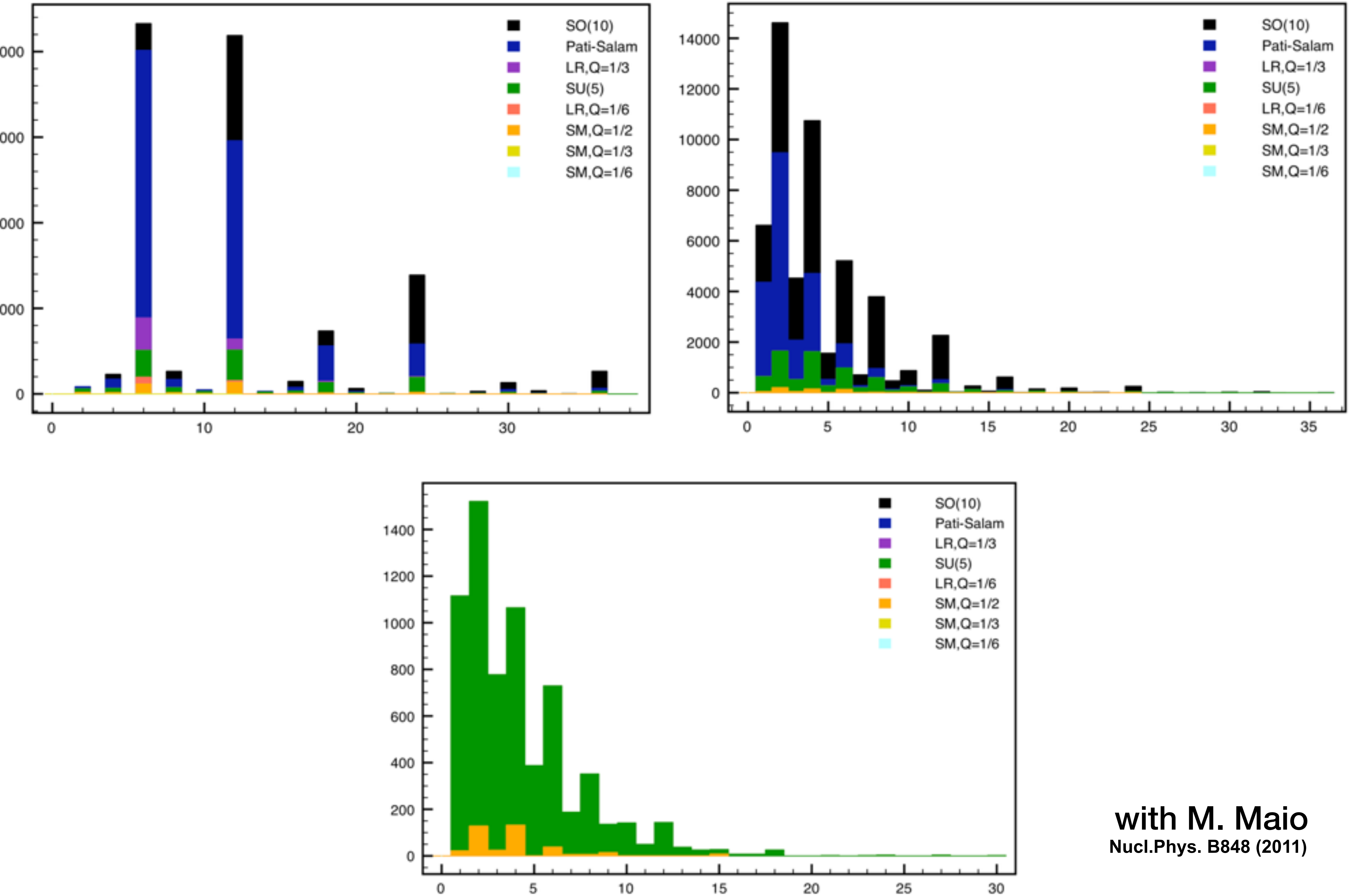


40000
30000
20000
10000
0
0
5
10
15
20
25
30
35
SU(5)
SM,Q=1/2
SM,Q=1/3
SM,Q=1/6

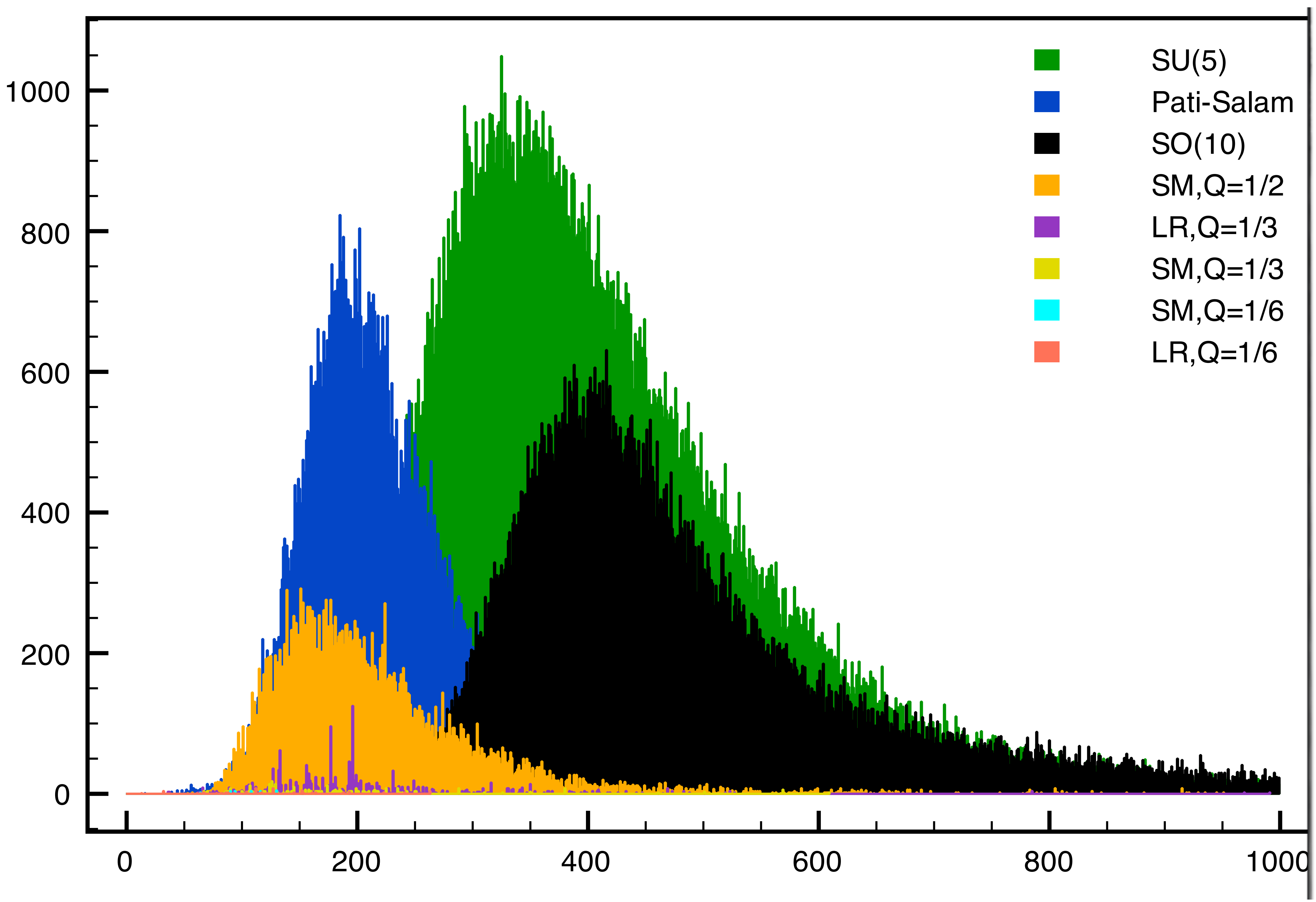


E8 splitting
A4 ⊕ A4 ⊕ (3,8,8,8)
A4 ⊕ A4 ⊕ (3,3,3,3,3)
A2 ⊕ E6 ⊕ (4,4,6,22)
0
20000
40000
60000
80000
0
5
10
15
20
25

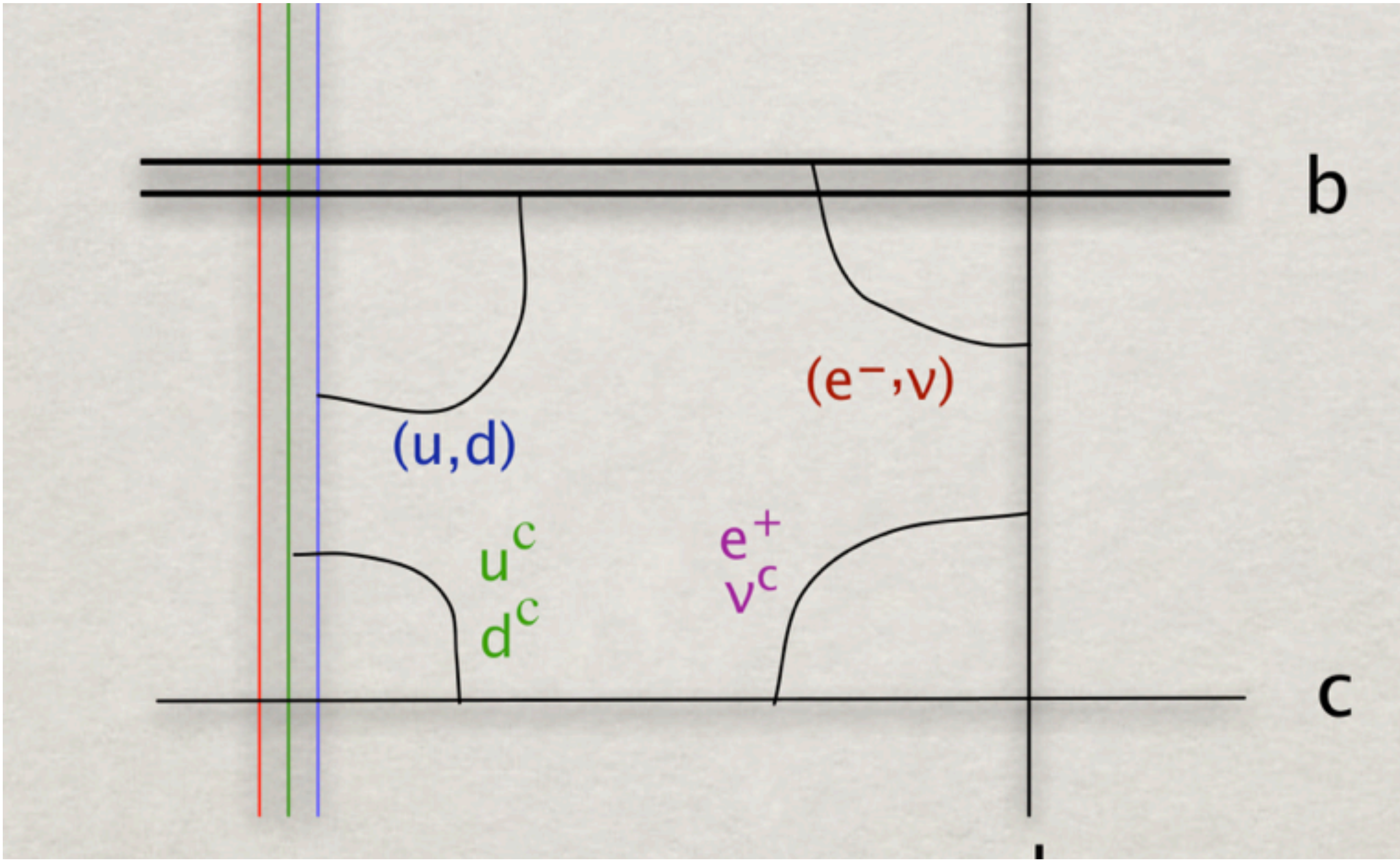
Permutations of Gepner Models



with M. Maio
Nucl.Phys. B848 (2011)



Number of singlets



Orientifolds

Combination (types)	Total number	Number searched	SMs found	Tadpoles solved
USUU (0+6)	187648179869355108	187171389940312068	1096682+49794	215846+4468
UUUU (1+7))	42766246654184825664	42730101309436185264	131704+1306	1280 + 0
USOU (2)	35594807811446520	21498035622653976	9474494	431633
UUOU (3)	2579563256116048068	720412912488220932	16891580	12533
USSU (4)	4486269786712304	2792296847030752	16227372	978200
UUSU (5)	187648179869355108	90192673747778532	1178970	5682
Total	45761187347637742772	43752168618082181524	45051902	1649642

Statistics of brane configurations

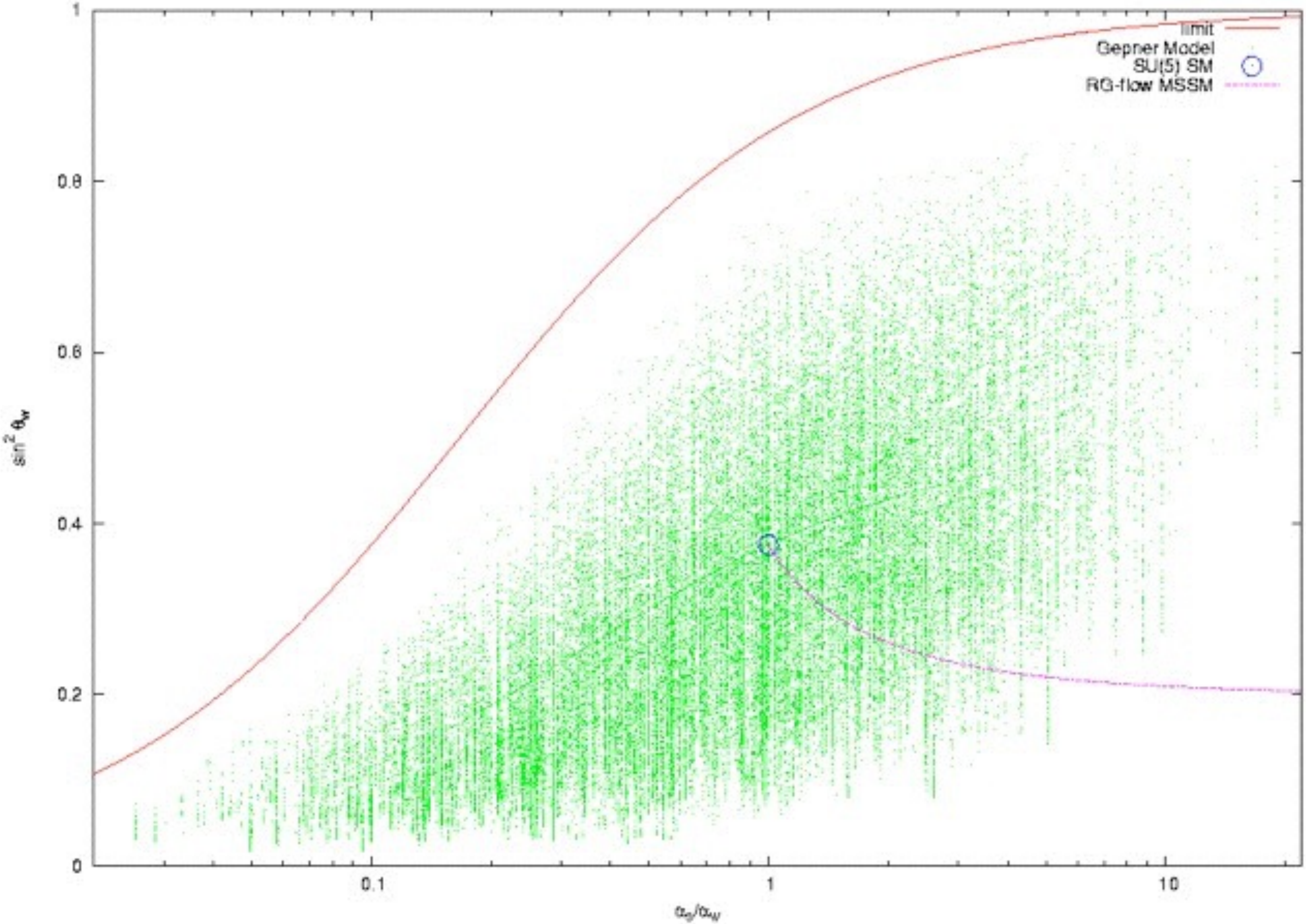
~ 10^{-14}

Dijkstra, Huiszoon, Schellekens Nucl.Phys. B710 (2005) 3-57

More general brane configuration search (but less complete search)

Anastasopoulos Dijkstra, Kiritsis, Schellekens, Nucl.Phys. B759 (2006) 83-146

From 8 chiral configurations to 19000!



limit
Gepner Model
SU(5) SM
RG-flow MSSM
1
0.8
0.6
0.4
0.2
0
0.1
1
10
$\sin^2\theta_W$
α_s/α_W

RCFT orientifolds with Standard Model Spectrum

Tim Dijkstra, Lennaert Huiszoon and Bert Schellekens

On this page you can search through all our supersymmetric, tadpole-free D=4, N=1 orientifold vacua with a three family chiral fermion spectrum identical to that of the Standard Model. They were constructed in a semi-systematic way by considering orientifolds of all Gepner Models (see *Phys.Lett.B609:408-417* and *Nucl.Phys.B710:3-57* for more information). Since the publication of these papers all spectra have been re-analysed and checked for the presence of global (Witten) anomalies. A few cases (less than 1%) needed correction. All spectra in this database are now free from global anomalies, and the total number is 211,634, slightly more than reported in these papers.

As explained in referenced articles the standard model gauge group can be realized in different ways (which we call *types*). In addition to these factors, the gauge group usually has extra *hidden* gauge group factors. Chiral states with one leg in the standard model gauge group are not permitted.
All these models of course have the same *chiral* spectrum for the standard model gauge group, except for the higgs-sector of which we do not know how it is realized in nature.

These models then differ in multiplicities of the non-chiral particles, hidden gauge group, higgs sector coupling constants on the string scale, and others.
To search for your favorite realization you can use the form below to filter our set with an condition. Example:

```
type==0 && nrHidden<2
```

You can consult a list of valid field names. Also much more complicated expressions are possible, see the syntax description.

Filter form

Two output formats are provided. The first only gives the number of answers, the second lists all the spectra satisfying the search criteria. Be warned that output can be very large and take up to a minute to compile; at the moment we have 211,634 models in the database, which means you can generate hundreds of MBs of output!

Filter condition

Output format

Number of models ⬍ Filter

```
Condition: type==6 && nrhidden=0

sh: /project/theorie/t58/MSSM_ARCHIVE/bin/filtersols_test: /lib/ld-linux.so.2: bad ELF interpreter: No such file or directory
```

Perspective ~2006

In 2018 we will have

- General agreement on the existence of a huge (> 10^{150}) dS landscape in string theory.
- Convincing arguments that the Standard Model, including its parameter values, exists somewhere in that landscape.
- A map of the most fertile areas
- A positive or negative prediction of low energy supersymmetry.

Perspective ~2006

In 2018 we will have

- General agreement on the existence of a huge ($> 10^{150}$) dS landscape in string theory. ✖
- Convincing arguments that the Standard Model, including its parameter values, exists somewhere in that landscape. ✖
- A map of the most fertile areas ✖
- A positive or negative prediction of low energy supersymmetry. ✖

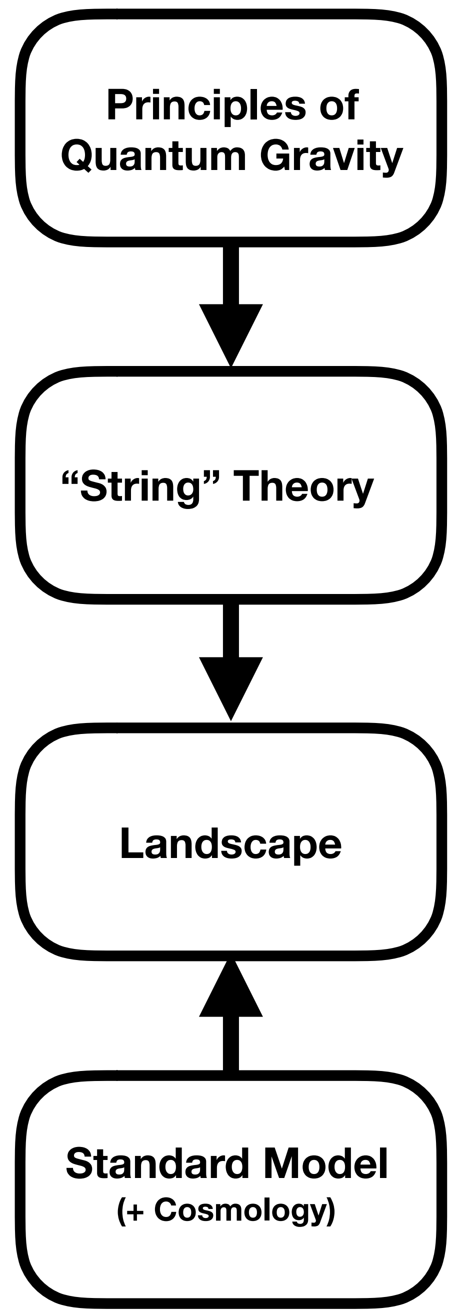
What keeps us going?

"String theory is an ultraviolet complete theory of quantum gravity that is a strong candidate for a unified theory of particle physics and cosmology"

Carifio, Cunningham, Halverson, Krioukov, Long, Nelson, arXiv:1711.06685

- **String theory "just works"**
- **Contains the Standard Model (gauge group and reps)**
- **<u>Has a connected landscape of vacua</u>**

How will we know it is true?



Black hole physics
Weak Gravity Conjecture
Swampland Conjectures
…..

Type II, Type I	(1971-1977)
Heterotic	(1984)
M-theory	(1995)
F-theory	(1996)
…..	

dS
Quintessence?
…

+ BSM

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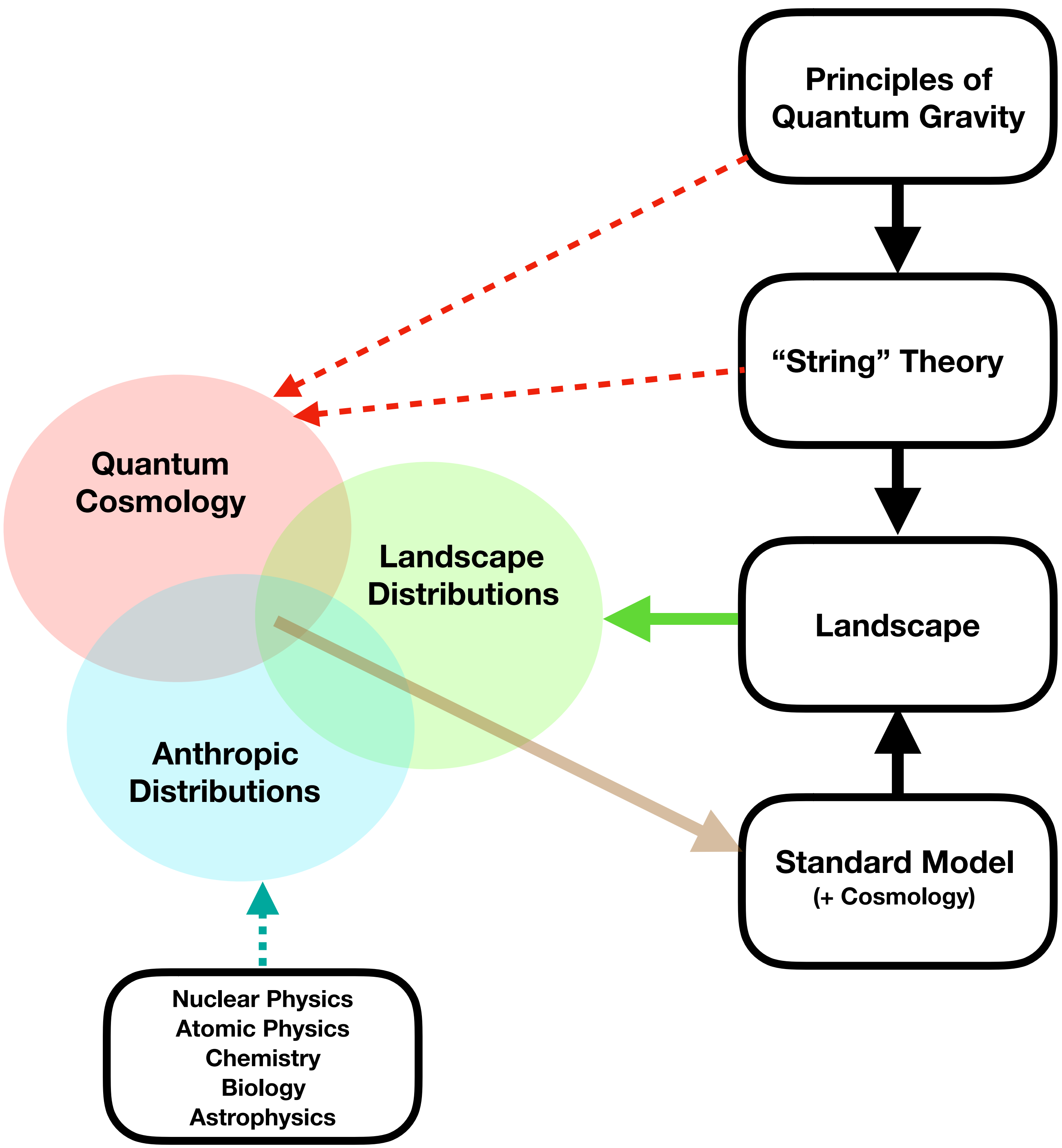

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Is the landscape too small?

$10^{272,000}$	(Taylor, Wang)
10^{501}	(Polchinski)
10^{500}	(Douglas,….)
10^{50}	(Bena,….)
1	(Gross,….)
0	(Vafa,….)

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Polchinksi: I have told Vafa that one of my life goals is to understand one of his papers, but no success yet.

The landscape is a humbling place….

$$10^{1500} < 10^{272000}$$

The landscape is a humbling place….

$$10^{1500} << 10^{272000}$$

The landscape is a humbling place….

10^{1500} <<<<<<<<<<<<<<<<<<<<<<<<<<<<<
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<<<<<<<<<<<<<<<<<<<<<<<<<<<< 10^{272000}

Is the landscape too large?

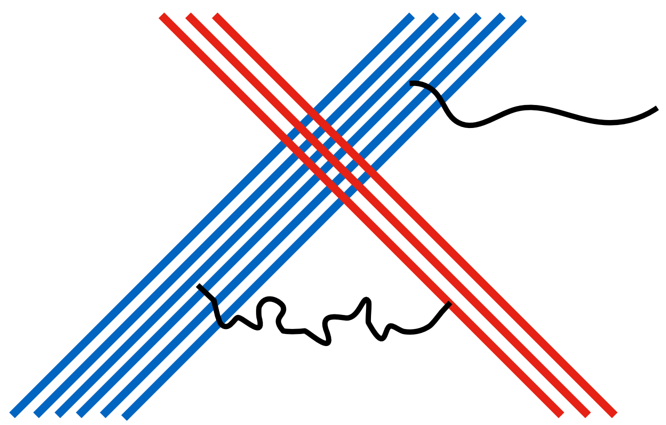
In the nice, cosy, Douglas landscape of a mere 10^{500} vacua we might still hope that the standard model stands out as being the simplest one with "atomic physics": electromagnetism, a substantial set of charges, and a hierarchy $m \ll m_{\mathrm{planck}}$

U(1) Simplest electromagnetic group

SU(3) Simplest group to build objects with a large spectrum of charges and with (almost) conserved baryon number ("nuclei")

SU(2) Remnant of hierarchy

Two stack models



$$SU(M) \times SU(N) \times U(1)$$

(assuming unitary branes)

$$Y = q_a Q_a + q_b Q_b$$

$q_a, \; q_b$ determined by axion couplings

Q	$(M, N, q_a + q_b)$
U	$(A, 1, 2q_a)$
D	$(\overline{M}, 1, -q_a)$
S	$(S, 1, 2q_a)$
X	$(M, \overline{N}, q_a - q_b)$
L	$(1, \overline{N}, -q_b)$
T	$(1, S, 2q_b)$
E	$(1, A, 2q_b)$

Nucl.Phys. B883 (2014) 529-580 with B. Gato Rivera

The Standard Model gauge group and family structure (N families) is the unique solution to these anthropic constraints, within the set of two-stack models.

This generalizes to multi-stack D-brane models, but with stronger simplicity assumptions.

But in F-theory?

$$E_8^{37} \times F_4^{85} \times G_2^{220} \times SU(2)^{320}$$

Carifio, Cunningham, Halverson, Krioukov, Long, Nelson, arXiv:1711.06685

Wrong landscape?

Is there a consistent, UV complete quintessence landscape that agrees with all current data? *(Sethi; Brennan, Carta, Vafa)*

If so, how large is it?

Non-susy strings?

Swampland constraints on SM phenomenology

Constraining Neutrino Masses, the Cosmological Constant and BSM Physics from the Weak Gravity Conjecture

Constraining the EW Hierarchy from the Weak Gravity Conjecture

Ibanez, Martin-Lozano,Valenzuela

AdS-phobia, the WGC, the Standard Model and Supersymmetry

Gonzalo, Alvaro Herráez, Ibanez

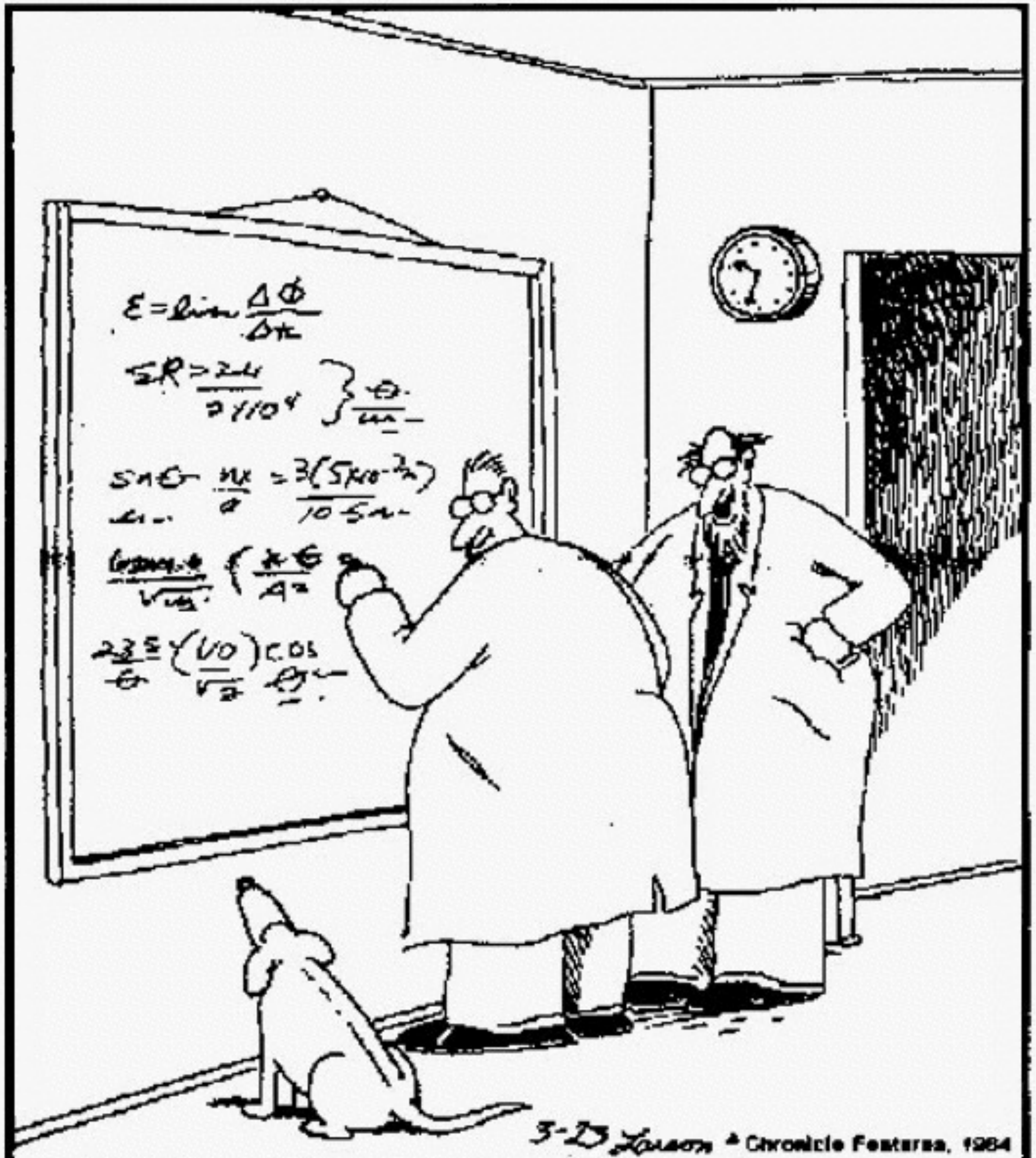
Weak Gravity Conjecture, Multiple Point Principle and the Standard Model Landscape

Hamada, Shiu

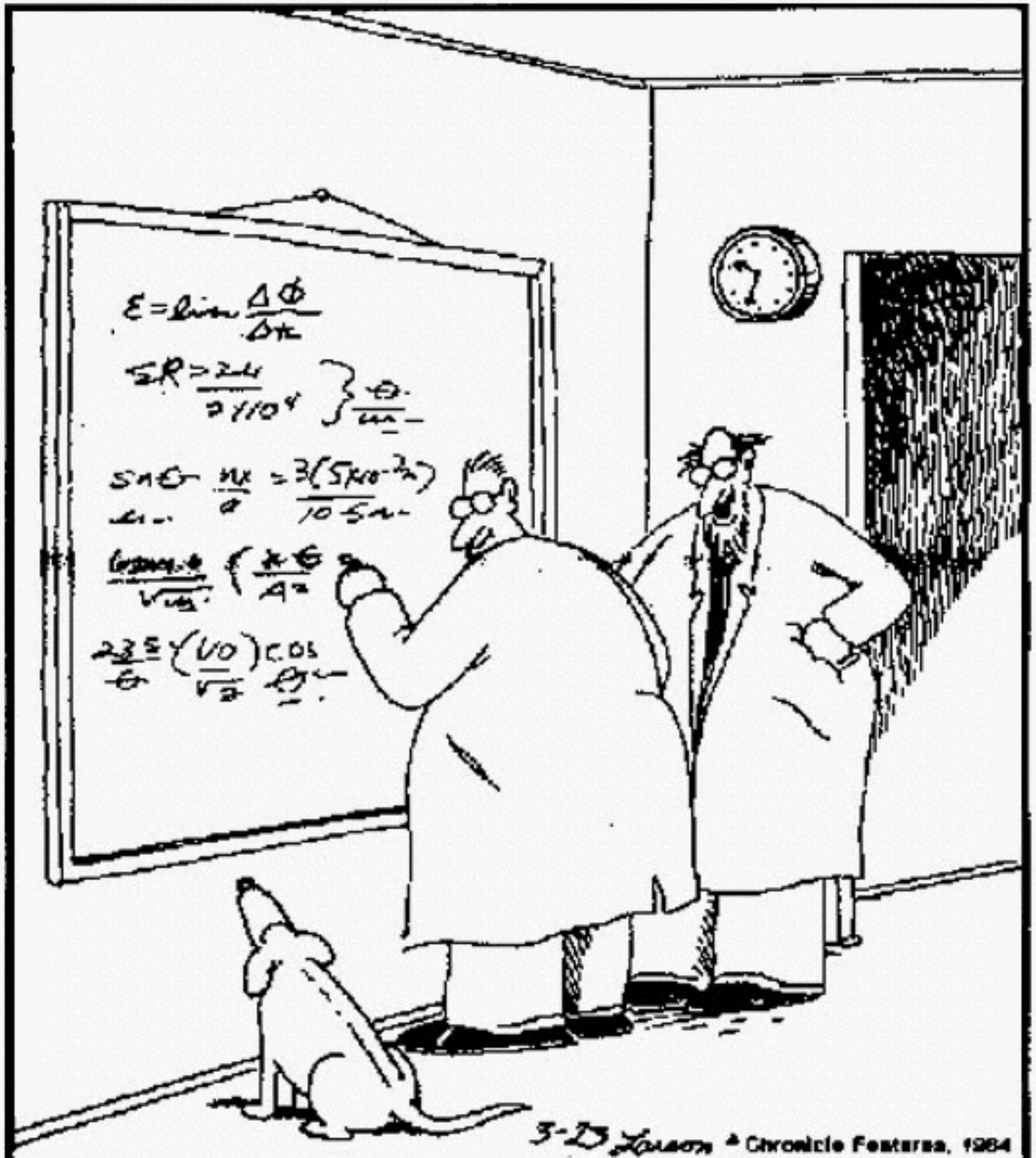
Perspective 2018

Machine learning will eventually solve this problem…

But will humans still be involved?



"Ohhhh ... Look at that, Schuster ... Dogs are so cute when they try to comprehend Quantum Mechanics".



"Ohhhh ... Look at that, Schuster ... Dogs are so cute when they try to comprehend Quantum Mechanics".

"Humans are so cute
when they try
to comprehend
the landscape"