Sightseeing in the Landscape

Contents

1984-2006: A Slow Revolution

- 1984: Hopes for Unification and Uniqueness
- 1985: Calabi-Yau manifolds, Narain Lattices, Orbifolds
- 1986: Fermionic and Bosonic constructions
- 1987: Gepner models
- ....
- 1995: M-theory compactifications, F-theory, Orientifolds
- ....
- 2003: Non-uniqueness got a name: The Landscape

M.Dine
hep-th/0402101

Faced with this plethora of states, I, for a long time, comforted myself that not a single example of a (meta)stable ground state of this sort had been exhibited in a controlled approximation, and so perhaps there might be some unique or at least limited set of sensible states.

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- Large number of vacua is **required** to explain Standard Model tuning

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- Therefore: A Success for String Theory*
- Enough vacua to explain cosmological constant and hierarchy tuning as well!
- Could be one of the great discoveries in the history of science (heliocentric model, theory of Evolution...)

*... if string theory is correct...

The three stages of scientific discovery

(Alexander von Humboldt)

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When people are confronted with an important discovery...

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The three stages of scientific discovery

(Alexander von Humboldt)

When people are confronted with an important discovery...

- First they deny that it is true
- Then they deny that it is important
- Then they credit the wrong people

Who cares,
just find the standard model....

The landscape "Drake Equation"

$$10^{500} \times 10^{-80} \times 10^{-120} = 10^{300}$$

Number of vacua

SM Probability

Cosmological
Constant

The landscape "Drake Equation"

$$10^{500} \times 10^{-80} \times 10^{-120} = 10^{300}$$

Number of vacua

SM Probability

Cosmological Constant

Not likely to yield 1!

So what can we still do?

- Explore unknown regions of the landscape
- Establish the likelyhood of standard model features (gauge group, three families, ...)
- Convince ourselves that standard model is a plausible vacuum
- Understand vacuum statistics
- Understand cosmological likelyhood
- Understand "anthropicity"

Orientifolds of Gepner Models

Earlier footprints

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

- Blumenhagen, Wisskirchen (1998)
  Non-chiral spectra from Gepner Orientifolds

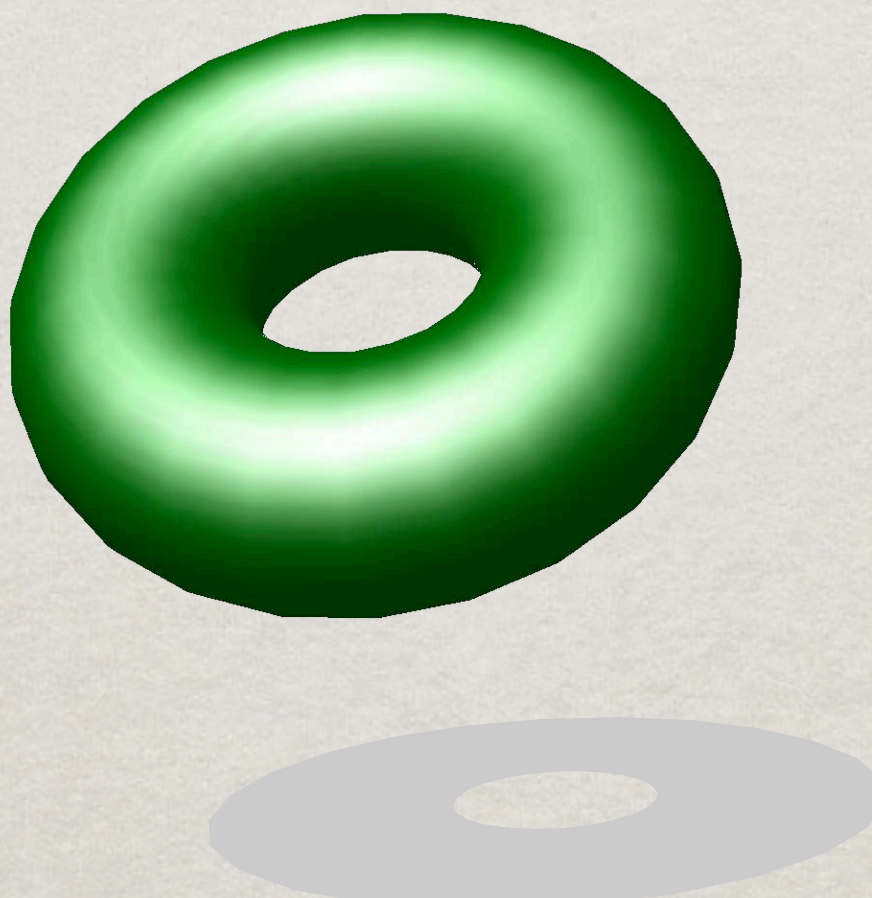
- Aldazabal, Franco, Ibanez, Rabadan, Uranga (2000)
  Blumenhagen,Görlich,Körs,Lüst (2000)
  Ibanez, Marchesano, Rabadan (2001)
  Non-supersymmetric SM-Spectra with RR tadpole cancellation

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

- Blumenhagen, Görlich, Ott (2002)
  Honecker (2003)

  Supersymmetric Pati-Salam Spectra with brane recombination

Closed String Partition Function



$$P(\tau, \bar{\tau}) = \sum_{ij} \chi_i(\tau) Z_{ij} \chi_j(\bar{\tau})$$

Orientifold Partition Functions

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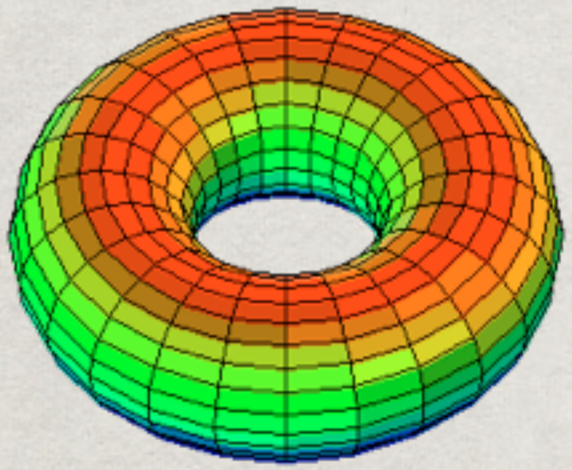
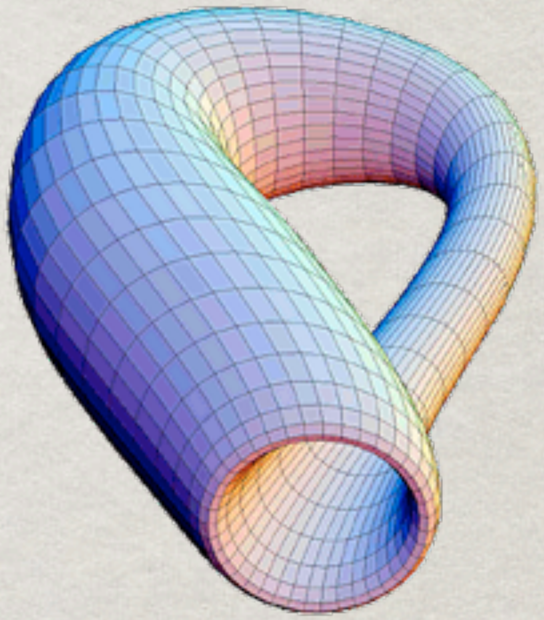
$\frac{1}{2}$ $\Big\{$

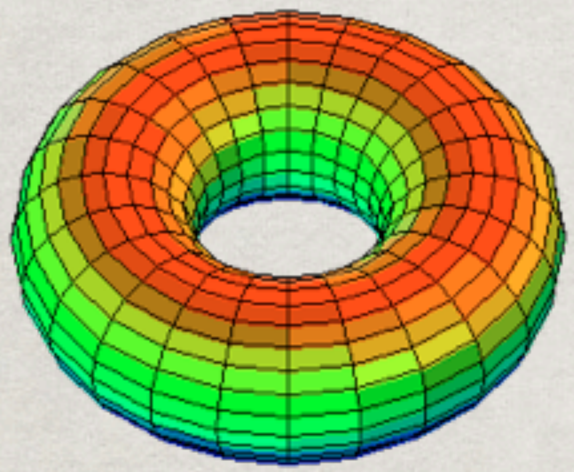
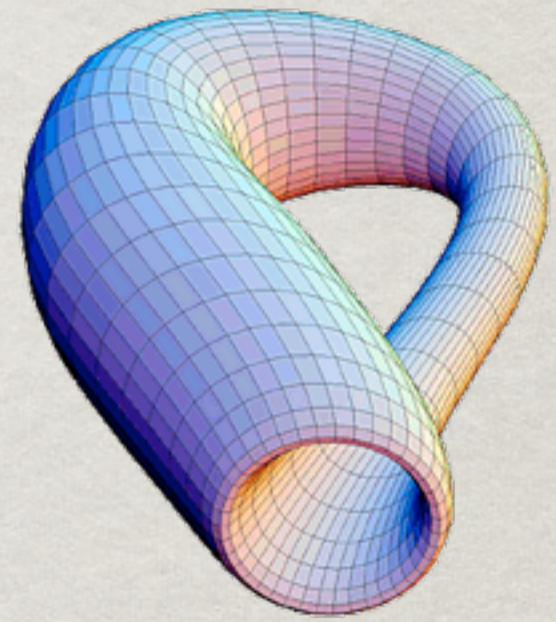


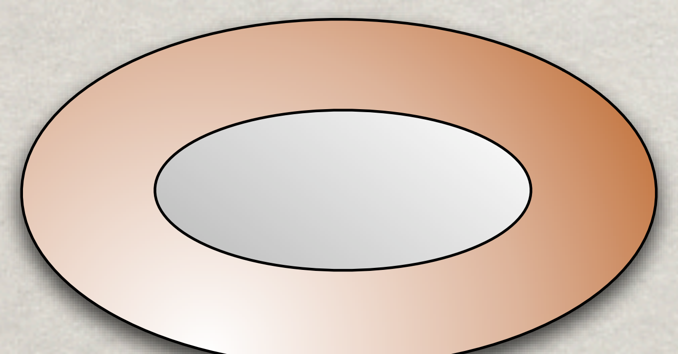
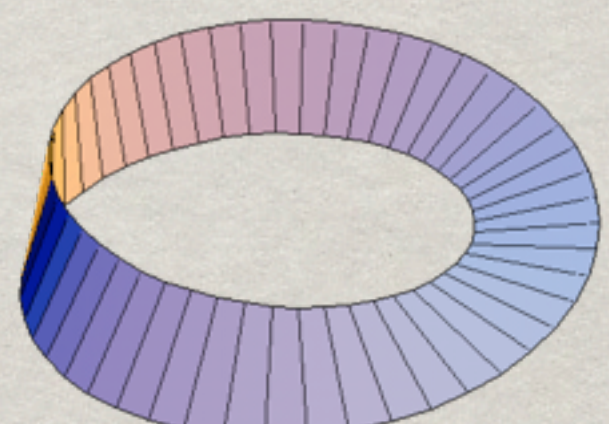
$+$



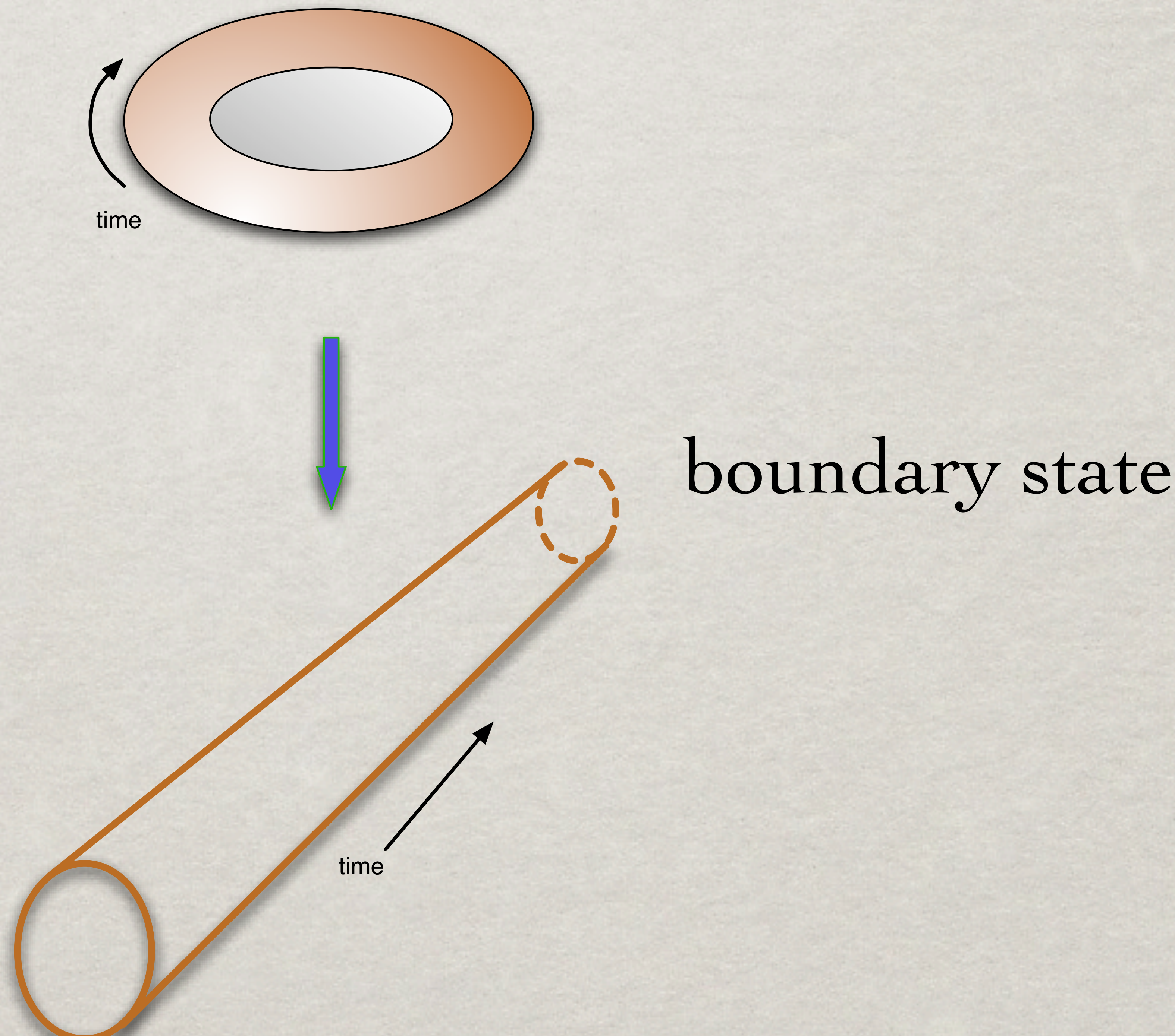
$\Big\}$

Orientifold Partition Functions

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

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

Transverse Channel



RCFT Orientifolds*

Data needed:

- A rational CFT with N=2 and $c = 9$
- The exact spectrum
- The modular matrix S

For simple current MIPFs:

- The "fixed point resolution matrices" S^J

**Pioneering work by Cardy; Sagnotti, Pradisi, Stanev; ...*

Formalism can be applied to:

- "Gepner Models"
  (minimal N=2 tensor products)
- Kazama-Suzuki models
  (requires exact spectrum computation)
- Permutation orbifolds
- ....

Gepner Models

Building Blocks:
Minimal N=2 CFT

$$c = \frac{3k}{k+2}, \quad k = 1, \ldots, \infty$$

168 ways of solving $\sum_i c_{k_i} = 9$

Spectrum:

$$h_{l,m} = \frac{l(l+2) - m^2}{4(k+2)} + \frac{s^2}{8}$$

$(l = 0, \ldots k; \quad q = -k, \ldots k+2; \quad s = -1, 0, 1, 2)$

(plus field identification)

$4(k+2)$ simple currents

Tensoring

- Preserve world-sheet susy
- Preserve space-time susy (GSO)
- Use surviving simple currents to build MIPFs
- This yields one point in the moduli space of a Calabi-Yau manifold

MIPFs*

- CFT has a discrete "simple current" group $\mathcal{G}$
  Choose a subgroup $\mathcal{H}$ of $\mathcal{G}$

- Choose a rational matrix $X_{\alpha\beta}$ obeying

$$\begin{aligned} 2X_{\alpha\beta} &= Q_{J_\alpha}(J_\beta) \text{ mod } 1, \alpha \neq \beta \\ X_{\alpha\alpha} &= -h_{J_\alpha} \\ N_\alpha X_{\alpha\beta} &\in \mathbb{Z} \text{ for all } \alpha, \beta \end{aligned}$$

$$Q_J(a) = h(a) + h(J) - h(Ja)$$

- This defines the torus partition function as

Z_{ij} is the number of currents $L \in \mathcal{H}$ such that

$$\begin{aligned} j &= Li \\ Q_M(i) + X(M, L) &= 0 \text{ mod } 1 \qquad \text{for all } M \in \mathcal{H}. \end{aligned}$$

*Gato-Rivera, Kreuzer, Schellekens (1991-1993)

orientifold Choices*

- "Klein bottle current" K (element of $\mathcal{H}$)
- "Crosscap signs" (signs defined on a subgroup of $\mathcal{H}$), satisfying

$$\beta_K(J)\beta_K(J') = \beta_K(JJ')e^{2\pi i X(J,J')} \quad , J, J' \in \mathcal{H}$$

Huiszoon, Sousa, Schellekens (1999-2000)

Boundaries and Crosscaps*

- Boundary coefficients

$$R_{[a,\psi_a](m,J)} = \sqrt{\frac{|\mathcal{H}|}{|\mathcal{C}_a||\mathcal{S}_a|}}\psi_a^*(J)S^J_{am}$$

- Crosscap coefficients

$$U_{(m,J)} = \frac{1}{\sqrt{|\mathcal{H}|}}\sum_{L\in\mathcal{H}}\eta(K,L)P_{LK,m}\delta_{J,0}$$

S^J is the *fixed point resolution matrix*
$\mathcal{S}_a$ is the *Stabilizer* of a
$\mathcal{C}_a$ is the *Central Stabilizer* ($\mathcal{C}_a \subset \mathcal{S}_a \subset \mathcal{H}$)
ψ_a is a discrete group character of $c\mathcal{C}_a$
$P = \sqrt{T}ST^2S\sqrt{T}$

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

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

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

N_a: Chan-Paton multiplicity

Coefficients

- Klein bottle

$$K^i = \sum_{m,J,J'} \frac{{S^i}_m U_{(m,J)} g^{\Omega,m}_{J,J'} U_{(m,J')}}{S_{0m}}$$

- Annulus

$$A^i_{[a,\psi_a][b,\psi_b]} = \sum_{m,J,J'} \frac{{S^i}_m R_{[a,\psi_a](m,J)} g^{\Omega,m}_{J,J'} R_{[b,\psi_b](m,J')}}{S_{0m}}$$

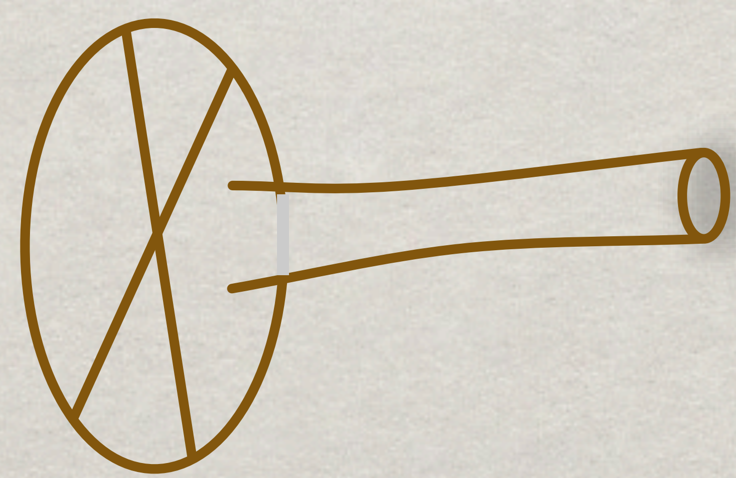
- Moebius

$$M^i_{[a,\psi_a]} = \sum_{m,J,J'} \frac{{P^i}_m R_{[a,\psi_a](m,J)} g^{\Omega,m}_{J,J'} U_{(m,J')}}{S_{0m}}$$

$$g^{\Omega,m}_{J,J'} = \frac{S_{m0}}{S_{mK}} \beta_K(J) \delta_{J',J^c}$$

tadpoles & Anomalies

tadpoles & Anomalies



tadpoles & Anomalies

Tadpoles & Anomalies

- Tadpole cancellation condition:

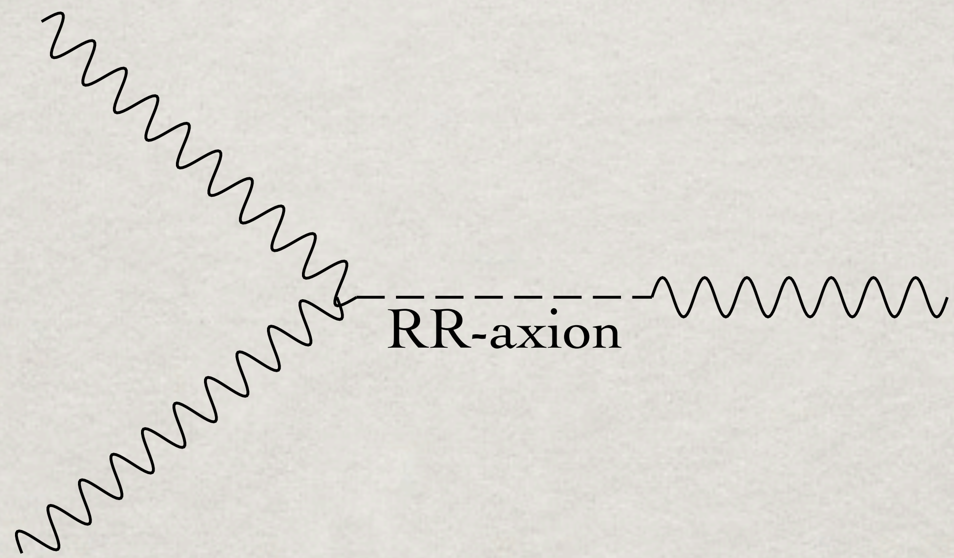
$$\sum_b N_b R_{b(m,J)} = 4\eta_m U_{(m,J)}$$

- Cubic $\mathrm{Tr} F^3$ anomalies cancel
- Remaining anomalies by Green-Schwarz mechanism
- In rare cases, additional conditions for global anomaly cancellation*

**Gato-Rivera, Schellekens (2005)*

Abelian Masses

Green-Schwarz mechanism



Axion-Vector boson vertex

Generates mass vector bosons of anomalous symmetries

$(e.g.\ B + L)$

But may also generate mass for non-anomalous ones

$(Y, B - L)$

Standard Model Search

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- 168 Gepner models

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- 5403 MIPFs

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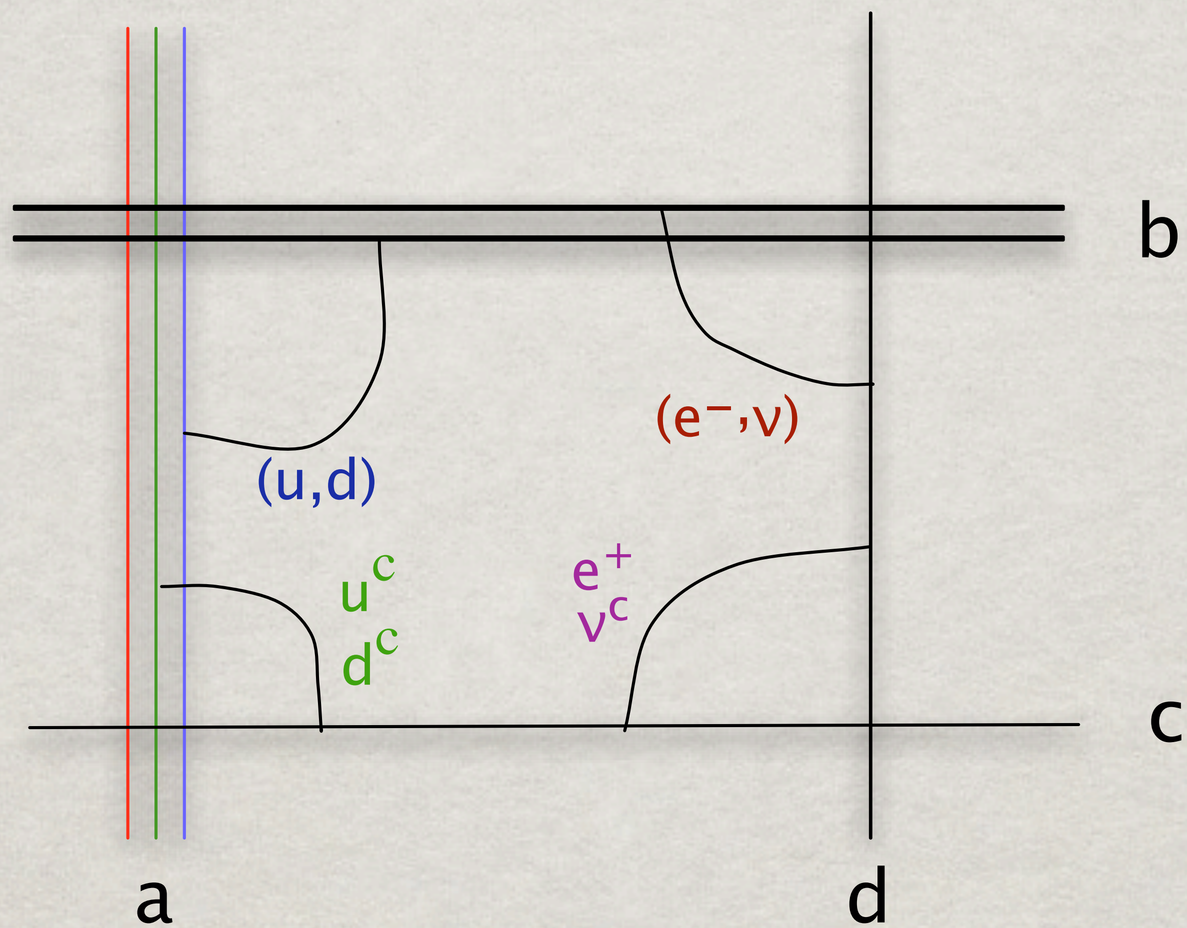
Essential to decide what to search for!

What to search for

The Madrid model



Chiral SU(3) x SU(2) x U(1) spectrum:

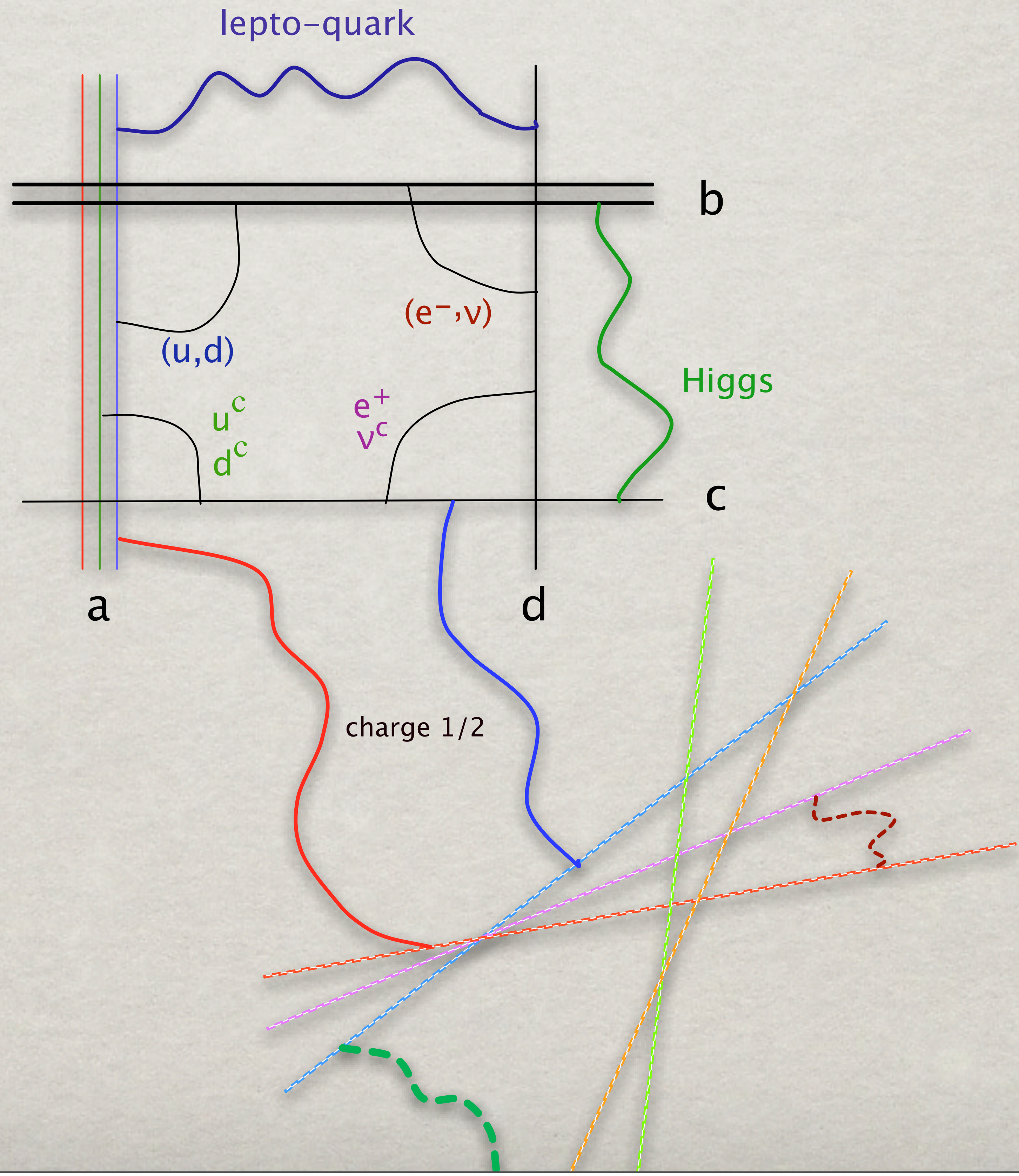
$$3(u,d)_L + 3u^c_L + 3d^c_L + 3(e^-,\nu)_L + 3e^+_L$$

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

N=1 Supersymmetry

No tadpoles, global anomalies

The hidden Sector



Chirality

Chan-Paton Group $\supset$ $SU(3) \times SU(2) \times U(1)$

- SM-chiral exotics are not allowed
- CP-nonchiral exotics are allowed
(mirror pairs, rank-2 tensors, adjoints, Higgs, lepto-quarks)
- CP-chiral, SM-nonchiral exotics occur,
but only rarely (Higgs, mirrors, singlets)
- Always three CP-chiral, SM-nonchiral
righthanded neutrinos

Non-chiral exotics may acquire mass under generic perturbations

Brane Configurations

Type	CP Group	B-L
0	U(3) x Sp(2) x U(1) x U(1)	massless
1	U(3) x U(2) x U(1) x U(1)	massless
2	U(3) x Sp(2) x O(2) x U(1)	massless
3	U(3) x U(2) x O(2) x U(1)	massless
4	U(3) x Sp(2) x Sp(2) x U(1)	massless
5	U(3) x U(2) x Sp(2) x U(1)	massless
6	U(3) x Sp(2) x U(1) x U(1)	massive
7	U(3) x U(2) x U(1) x U(1)	massive

Results (2004)*

- Solutions to Tadpole conditions for 44/168 Gepner models, 333/5403 MIPFs
- Total number of 4 stacks with SM spectrum: 45×10^{6} (out of 45×10^{18})
- Total number of 4 stacks with tadpole solutions: 1.6×10^{6}
- Total number of distinct SM spectra: 1.8×10^{5}
  (counting non-chiral, but the not hidden sector)
- No solutions for C-invariant
- No solutions for orbifolds
- No solutions for quintic

**T. Dijkstra, L. Huiszoon, A. Schellekens Nucl.Phys.B710:3-57,2005*

STATISTICS

Total number of 4-stack configurations	45761187347637742772 (45.7×10^{18})
Total number scanned	4.37522E+19
Total number of SM configurations	45051902 fraction: 1.0×10^{-12}
Total number of tadpole solutions	1649642 fraction: 3.8×10^{-14} (*)
Total number of distinct solutions	211634

(*) cf. Gmeiner, Blumenhagen, Honecker, Lüst, Weigand: "One in a Billion"

Type Distribution

Type	Quark*	Lepton*	Higgs*	Nr.
0	0	0	0	10564
1	-3	3	0	32
1	-9	3	6	1
1	-9	9	0	22
2	0	0	0	49661
3	-3	-1	4	141
3	-3	-3	6	24
3	-3	1	2	240
3	-3	3	0	740
3	-9	-3	12	24
3	-9	3	6	95
3	-9	5	4	1
3	-9	9	0	116
4	0	0	0	116304
5	-3	1	2	2
5	-3	3	0	1507
5	-9	9	0	46

Type 6 (Massive B-L, Type 0): 403
Type 7 (Massive B-L, Type 1): 0
No extra branes: 1270
Massive B-L, No extra branes: 22 (just SU(3)xSU(2)xU(1)!)

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 210,782, 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

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Filter condition

```
udmir=0 && umir==0 && dmir==0 && enmir==0 && emir==0 && nmir==0 &&
aadj==0 && badj==0 && cadj==0 && dadj==0 &&
aa==0 && ba==0 && ca==0 && da==0
&& as==0 && bs==0 && cs==0&& ds==0
```

Output format

Summary for each model | Filter

```
Number of representations: 19

3 x (V ,V ,0 ,0 ,0 ,0 ,0 ) chirality 3
3 x (V ,0 ,V ,0 ,0 ,0 ,0 ) chirality -3
3 x (0 ,V ,0 ,V ,0 ,0 ,0 ) chirality 3
3 x (0 ,0 ,V ,V ,0 ,0 ,0 ) chirality -3
2 x (V ,0 ,0 ,V ,0 ,0 ,0 )
2 x (0 ,V ,V ,0 ,0 ,0 ,0 )
2 x (V ,0 ,0 ,0 ,V ,0 ,0 )
2 x (V ,0 ,0 ,0 ,0 ,V ,0 )
2 x (V ,0 ,0 ,0 ,0 ,0 ,V )
1 x (0 ,V ,0 ,0 ,V ,0 ,0 )
1 x (0 ,0 ,V ,0 ,V ,0 ,0 )
2 x (0 ,0 ,0 ,V ,0 ,V ,0 )
1 x (0 ,0 ,0 ,0 ,V ,0 ,V )
2 x (0 ,0 ,0 ,0 ,0 ,V ,V )
2 x (0 ,0 ,0 ,0 ,A ,0 ,0 )
1 x (0 ,0 ,0 ,0 ,S ,0 ,0 )
5 x (0 ,0 ,0 ,0 ,0 ,A ,0 )
5 x (0 ,0 ,0 ,0 ,0 ,S ,0 )
1 x (0 ,0 ,0 ,0 ,0 ,0 ,S )

                         Summary:
      Higgs: (2,1/2)+(2*,1/2)                    2
Non-chiral SM matter (Q,U,D,L,E,N):  0  0  0  0  0  0
   Adjoints:                            0  0  0  0
   Symmetric Tensors:                   0  0  0  0
   Anti-Symmetric Tensors:              0  0  0  0
      Lepto-quarks: (3,-1/3),(3,2/3)       1  0
   Non-SM (a,b,c,d)                    12  6  6  4
Hidden (Total dimension)             162 (chirality 0)
```

$\sin^2(\theta_w) = .3610368$

$\frac{\alpha_3}{\alpha_2} = .8660246$

```
Standard model type: 6
Number of factors in hidden gauge group: 0
Gauge group: U(3) x Sp(2) x U(1) x U(1)

Number of representations: 19

 3 x  (V ,V ,0 ,0 ) chirality 3
 3 x  (V ,0 ,V ,0 ) chirality -3
 3 x  (V ,0 ,V*,0 ) chirality -3
 9 x  (0 ,V ,0 ,V ) chirality 3
 5 x  (0 ,0 ,V ,V ) chirality -3
 3 x  (0 ,0 ,V ,V*) chirality
 2 x  (V ,0 ,0 ,V )
10 x  (0 ,V ,V ,0 )
 2 x  (Ad,0 ,0 ,0 )
 2 x  (A ,0 ,0 ,0 )
```

•••••••

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 2 x  (V ,0 ,0 ,V )
10 x  (0 ,V ,V ,0 )
 2 x  (Ad,0 ,0 ,0 )
 2 x  (A ,0 ,0 ,0 )
```

•••••••

```
     Higgs:   (2,1/2)+  2*,1/2)              5
Non-chiral SM matter   (Q,U,D,L,E,N):  0  0  0  3  1  0
  Adjoints:                            2  0  9  3
  Symmetric Tensors:                   1 10  7  3
  Anti-Symmetric Tensors:              1 14  3  2
    Lepto-quarks:   3,-1/3),  3,2/3)      1  0
 Non-SM   a,b,c,d)                      0  0  0  0
 Hidden   Total dimension)              0   (chirality 0)
```

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```
    Higgs:   (2,1/2)+  2*,1/2)              5
Non-chiral SM matter   (Q,U,D,L,E,N):  0  0  0  3  1  0
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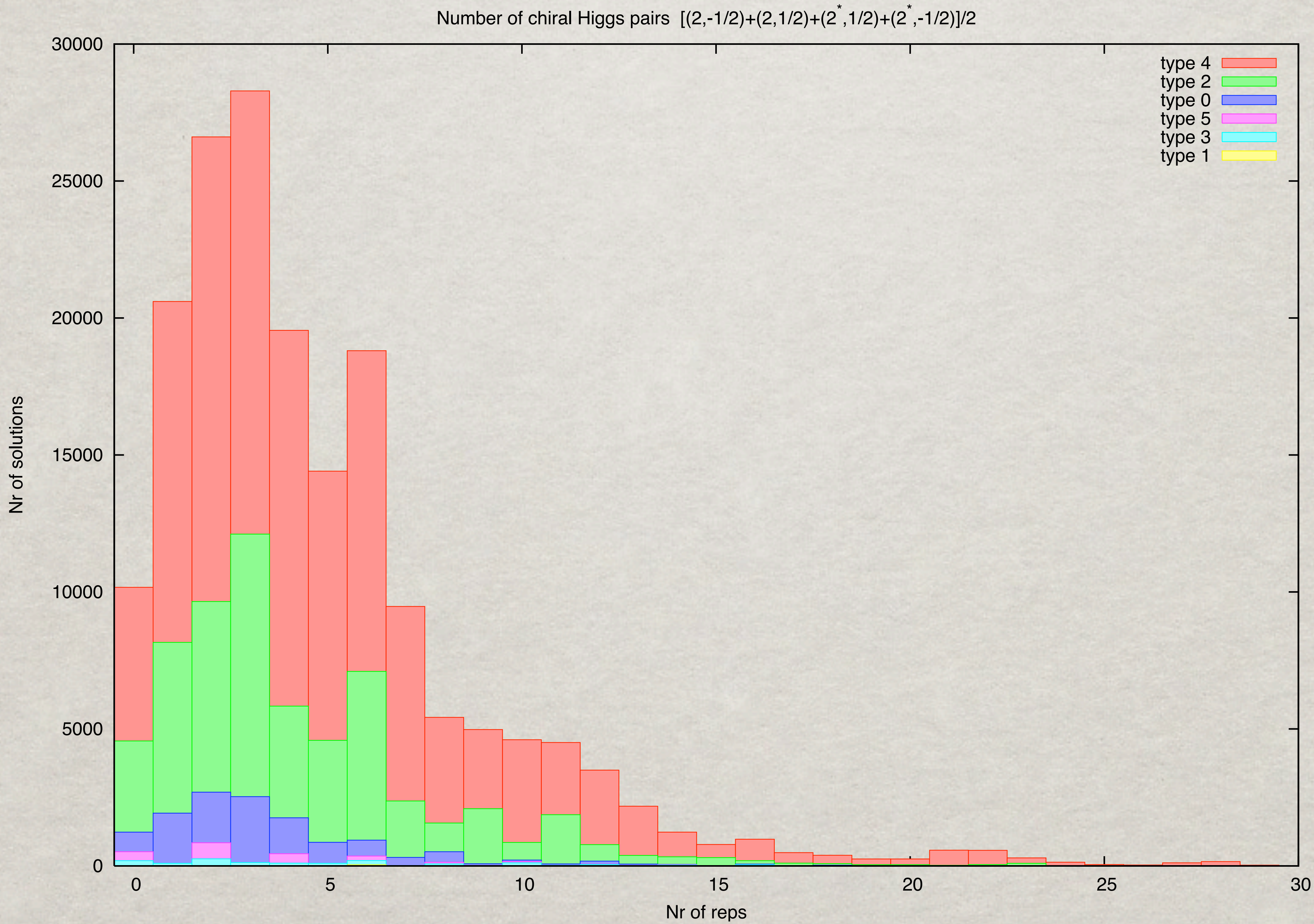
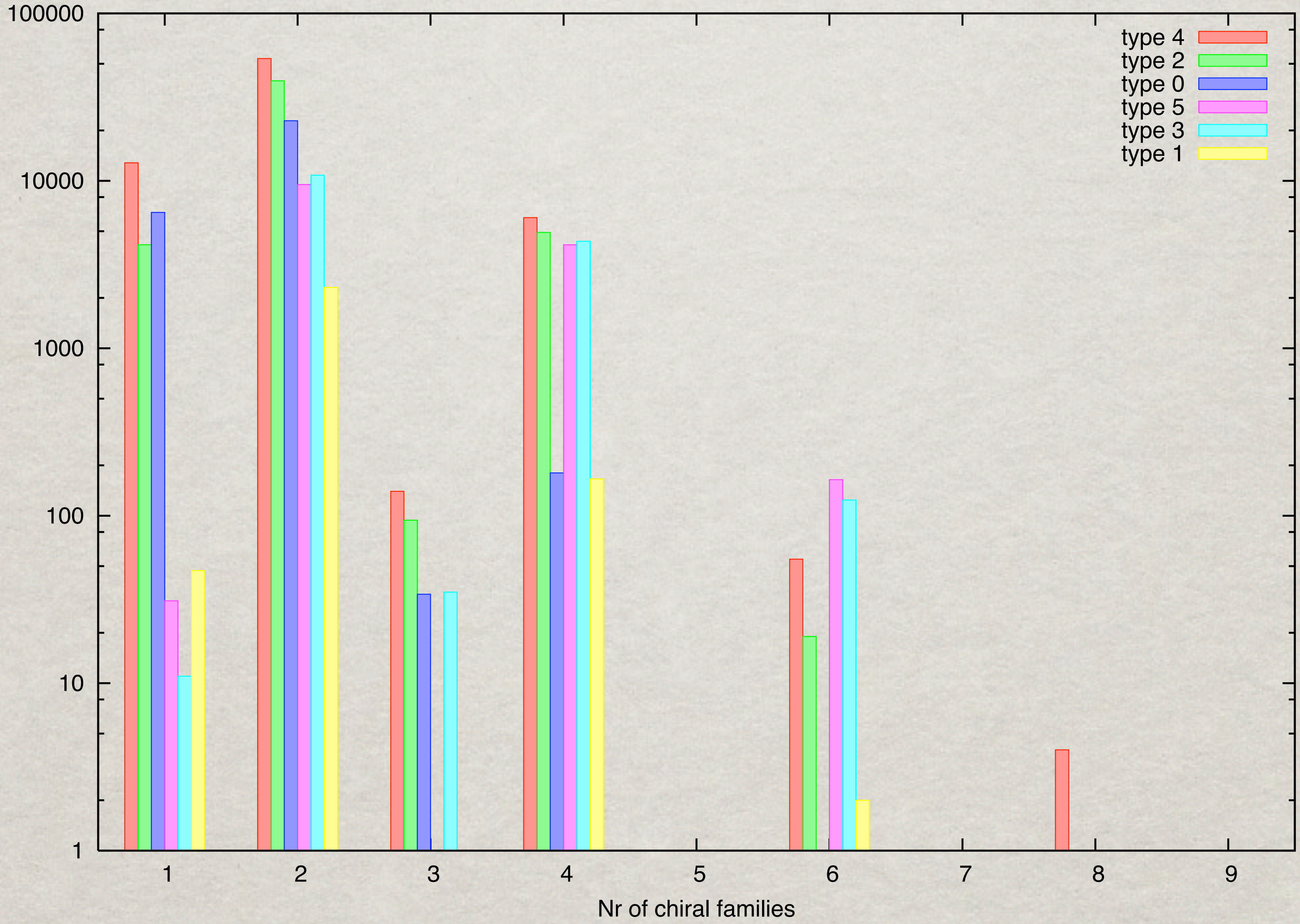
  Anti-Symmetric Tensors:              1 14  3  2
    Lepto-quarks:   3,-1/3),  3,2/3)      1  0
 Non-SM    a,b,c,d)                     0  0  0  0
 Hidden    Total dimension)             0   (chirality 0)
```

$$\sin^2(\theta_w) = .5271853$$

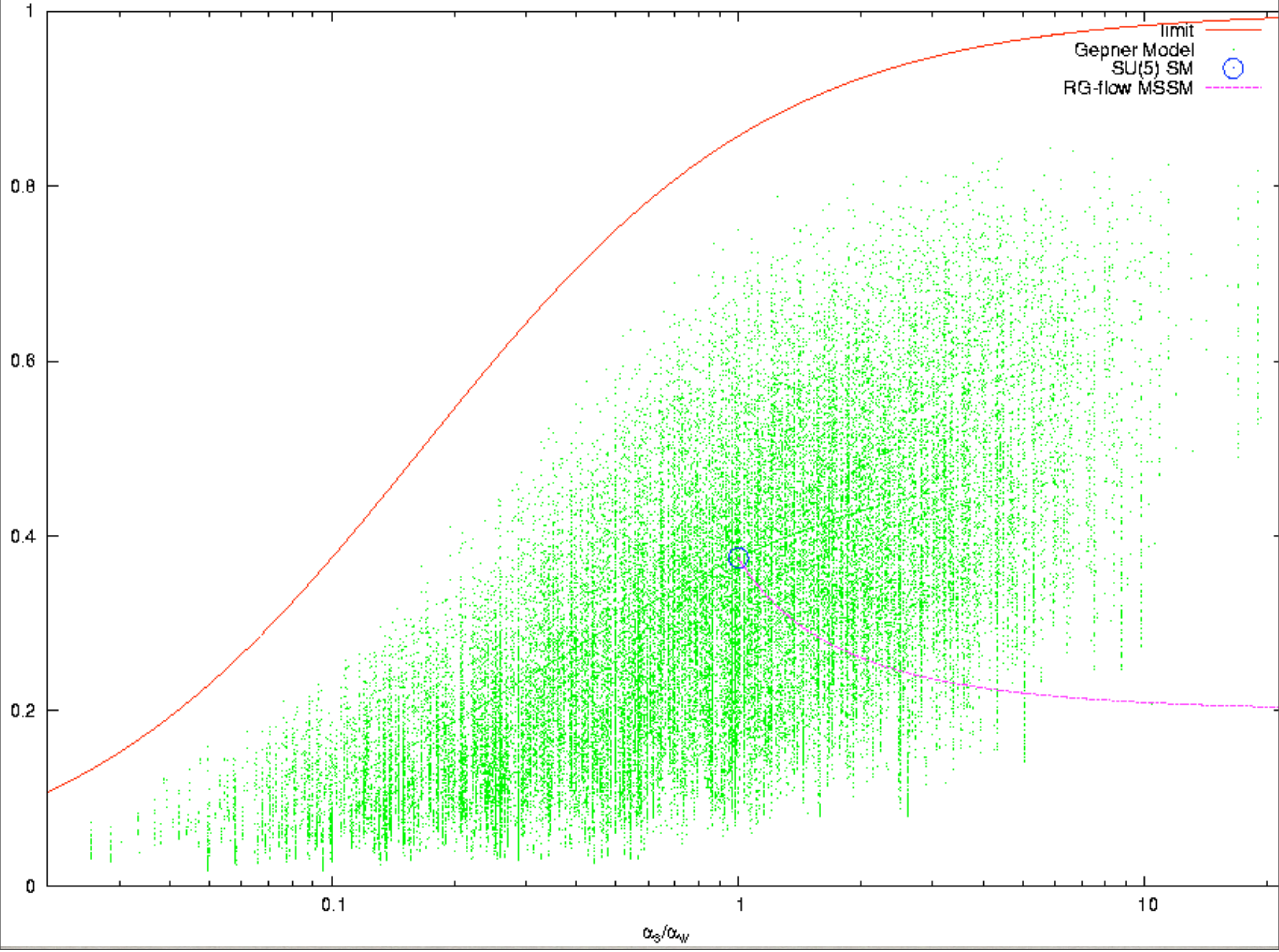
$$\frac{\alpha_3}{\alpha_2} = 3.2320501$$

Higgs Distribution





100000
10000
1000
100
10
1
1
2
3
4
5
6
7
8
9
Nr of chiral families
type 4
type 2
type 0
type 5
type 3
type 1



limit
Gepner Model
SU(5) SM
RG-flow MSSM
1
0.8
0.6
0.4
0.2
0
0.1
1
10
α_s/α_W

Unbiased search*

Require only:

- U(3) from a single brane
- U(2) from a single brane
- Quarks and leptons, Y from at most four branes
- $G_{CP} \supset SU(3) \times SU(2) \times U(1)$
- Chiral G_{CP} fermions reduce to quarks, leptons (plus non-chiral particles) but
- No fractionally charged mirror pairs
- Massless Y

P. Anastasopoulos, T. Dijkstra, E. Kiritsis, A.N.S, in (slow) progress

Allowed Features

- (Anti)-quarks from anti-symmetric tensors
- leptons from anti-symmetric tensors
- family symmetries
- non-standard Y-charge assignments
- Unification (Pati-Salam, (flipped) SU(5), trinification)*
- Baryon and/or lepton number violation
- ....

*a,b,c,d may be identical

Chan-Paton gauge group

$$G_{CP} = U(3)_a \times \left\{ \begin{array}{c} U(2)_b \\ Sp(2)_b \end{array} \right\} \times G_c \qquad (\times G_d)$$

Embedding of Y:

$$Y = \alpha Q_a + \beta Q_b + \gamma Q_c + \delta Q_d + W_c + W_d$$

Q: Brane charges (for unitary branes)

W: Traceless generators

Classification

$$Y = (x - \frac{1}{3})Q_a + (x - \frac{1}{2})Q_b + \underbrace{xQ_C + (x-1)Q_D}$$

Distributed over
c and d

Allowed values for x

1/2	Madrid model, Pati-Salam, Flipped SU(5)
0	(broken) SU(5)
1	
-1/2, 3/2	
any	Trinification ($x = 1/3$)

The basic orientable model

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

$3 \times (V, V^*, 0, 0)$	(u,d)
$3 \times (V^*, 0, V, 0)$	d^c
$3 \times (V^*, 0, 0, V)$	u^c
$6 \times (0, V, V^*, 0)$	$(e^-, \nu) + H_1$
$3 \times (0, V, 0, V^*)$	H_2
$3 \times (0, 0, V, V^*)$	e^+

Results

- Searched all MIPFs with < 1750 boundaries (4557 of 5403 MIPFs)
- 19345 chirally different SM embeddings found
- Tadpole conditions solved in 1900 cases (18 “old” ones)

Statistics

Value of x	Total
0	24483441
1/2	138764372*
1	30580
-1/2, 3/2	0
any	1250080

*Previous search: 45051902

BOTTOM-UP vs TOP-DOWN (1)

x	Config.	stack **c**	stack **d**	Bottom-up	Top-down	Occurrences	Solved
1/2	UUUU	C,D	C,D	54	9	5194	1
1/2	UUUU	C	C,D	206670	433	1311628	31
1/2	UUUU	C	C	21284680	156	758098	24
1/2	UUU	C,D	-	8	1	24	0
1/2	UUU	C	-	408	5	26210	2
1/2	UUUR	C,D	C,D	68	5	3888	1
1/2	UUUR	C	C,D	369813	221	3121585	31
1/2	USUU	C,D	C,D	144	7	6473	2
1/2	USUU	C	C,D	305858	283	6268942	33
1/2	USUU	C	C	20073902	125	7310339	27
1/2	USU	C	-	104	2	222	0
1/2	USU	C,D	-	16	1	4881	1
1/2	USUR	C	C,D	106484	31	49807425	19
1/2	USUR	C,D	C,D	72	2	858330	2

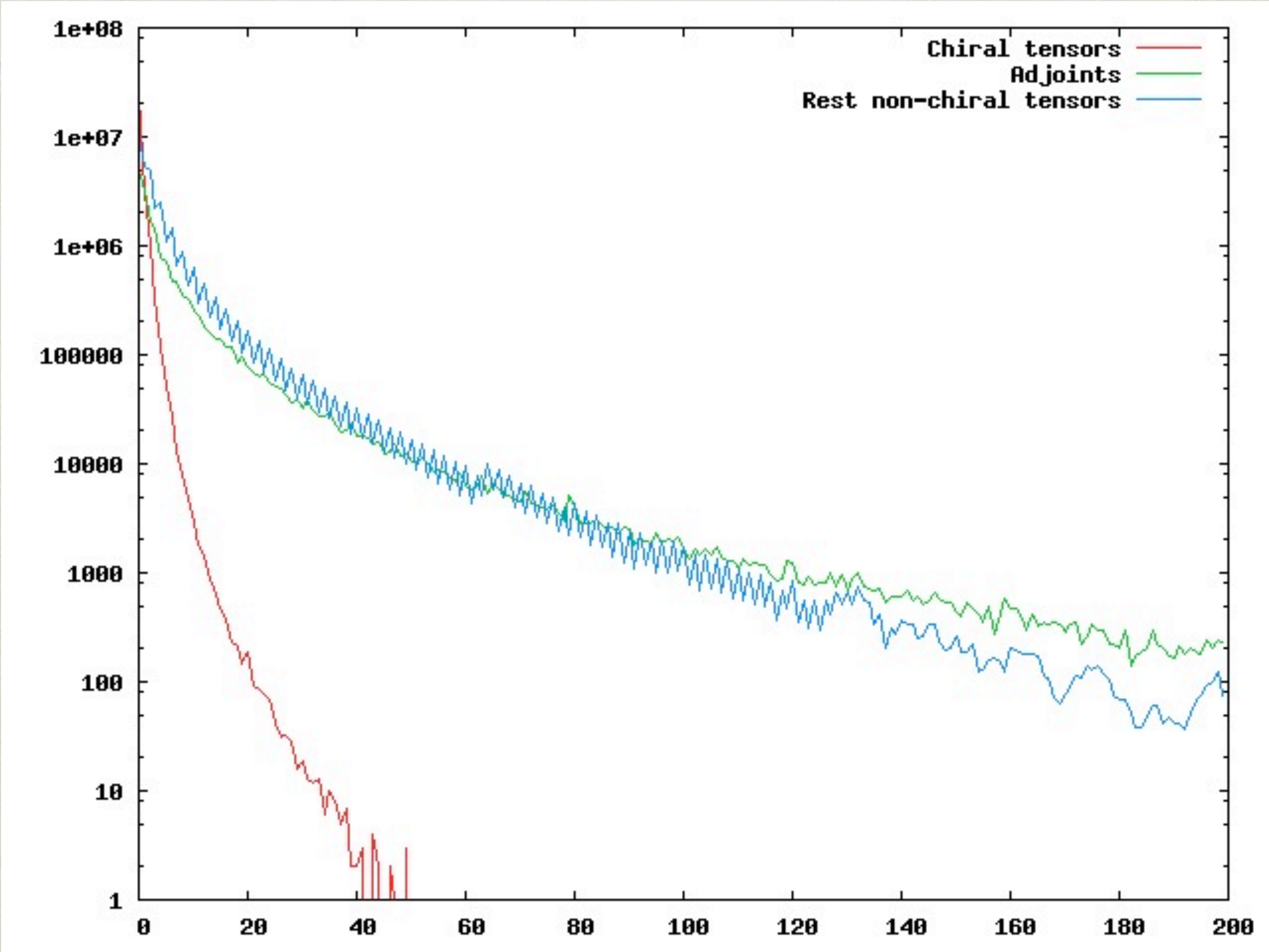
Bottom-up vs Top-down (2)

0	UUUU	C,D	C,D	10	5	4530	2
0	UUUU	C	C,D	16662	44	69956	2
0	UUUU	D	C,D	28	2	6480	0
0	UUUU	C	C	5778108	127	847924	9
0	UUUU	C	D	69772	16	6809	0
0	UUU	C	-	424	2	28340	1
0	UUUR	C,D	C	7238	39	171485	4
0	UUUR	C	C	10307393	289	5380920	32
0	UUUR	D	C	8564	22	50748	0
0	UUR	C	-	58	2	233071	2
0	UURR	C	C	24091	17	8452983	17

Bottom-up vs Top-down (3)

1	UUUU	C,D	C,D	8	1	1144	1
1	UUUU	C	C,D	32	5	25958	0
1	UUUU	D	C,D	84	3	5440	0
1	UUUU	C	D	1669	0	0	0
1	UUUR	C,D	D	68	1	1024	0
1	UUUR	C	D	609	1	640	0
3/2	UUUU	C	D	9	0	0	0
3/2	UUUU	C,D	D	2	0	0	0
3/2	UUUU	C, D	C	20	0	0	0
3/2	UUUU	C,D	C,D	4	0	0	0
$*$	UUUU	C,D	C,D	4	2	5146	1
$*$	UUUU	C	C,D	20	7	521372	3
$*$	UUUU	D	C,D	2	1	116	0
$*$	UUUU	C	D	3	1	4	0

Chiral tensor suppression



Most frequent models

nr.	Total occ.	MIPFs	Chan-Paton group	Spectrum	x	Solved
1	9785532	647	$U(3) \times Sp(2) \times Sp(6) \times U(1)$	VVVV	1/2	Y!
2	8459664	674	$U(3) \times Sp(2) \times Sp(2) \times U(1)$	VVVV	1/2	Y!
3	5769030	820	$U(4) \times Sp(2) \times Sp(6)$	VVV	1/2	Y!
4	4801518	867	$U(4) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!
5	4751603	554	$U(3) \times Sp(2) \times O(6) \times U(1)$	VVVV	1/2	Y!
6	4584392	751	$U(4) \times Sp(2) \times O(6)$	VVV	1/2	Y
7	4509752	513	$U(3) \times Sp(2) \times O(2) \times U(1)$	VVVV	1/2	Y!
8	3744864	690	$U(4) \times Sp(2) \times O(2)$	VVV	1/2	Y!
9	3603236	466	$U(3) \times Sp(2) \times Sp(6) \times U(3)$	VVVV	1/2	Y
10	3308076	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
11	3308076	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
12	3091021	622	$U(6) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
13	2713960	460	$U(3) \times Sp(2) \times Sp(2) \times U(3)$	VVVV	1/2	Y!
14	2384626	560	$U(6) \times Sp(2) \times O(6)$	VVV	1/2	Y
15	2250118	668	$U(6) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!
16	1803909	519	$U(6) \times Sp(2) \times O(2)$	VVV	1/2	Y!
17	1787210	486	$U(4) \times Sp(2) \times U(3)$	VVV	1/2	Y
18	1787210	486	$U(4) \times Sp(2) \times U(3)$	VVV	1/2	Y
19	1674989	516	$U(8) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
20	1674416	384	$U(3) \times Sp(2) \times O(6) \times U(3)$	VVVV	1/2	Y
21	1641845	359	$U(3) \times Sp(2) \times Sp(6) \times U(5)$	VVVV	1/2	Y
22	1486664	346	$U(3) \times Sp(2) \times O(2) \times U(3)$	VVVV	1/2	Y!
23	1323363	476	$U(8) \times Sp(2) \times O(6)$	VVV	1/2	Y
24	1135044	349	$U(3) \times Sp(2) \times Sp(2) \times U(5)$	VVVV	1/2	Y!
25	1106616	209	$U(3) \times Sp(2) \times U(3) \times U(3)$	VVVV	1/2	Y
26	1106616	209	$U(3) \times Sp(2) \times U(3) \times U(3)$	VVVV	1/2	Y
27	1049176	531	$U(8) \times Sp(2) \times Sp(2)$	VVV	1/2	Y
28	956980	421	$U(8) \times Sp(2) \times O(2)$	VVV	1/2	Y
29	949189	448	$U(10) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
30	935034	351	$U(6) \times Sp(2) \times U(3)$	VVV	1/2	Y
31	935034	351	$U(6) \times Sp(2) \times U(3)$	VVV	1/2	Y
32	910132	51	$U(3) \times U(2) \times Sp(2) \times O(1)$	AAVV	0	Y

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2	8459664	674	$U(3) \times Sp(2) \times Sp(2) \times U(1)$	VVVV	1/2	Y!
3	5769030	820	$U(4) \times Sp(2) \times Sp(6)$	VVV	1/2	Y!
4	4801518	867	$U(4) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!
5	4751603	554	$U(3) \times Sp(2) \times O(6) \times U(1)$	VVVV	1/2	Y!
6	4584392	751	$U(4) \times Sp(2) \times O(6)$	VVV	1/2	Y
7	4509752	513	$U(3) \times Sp(2) \times O(2) \times U(1)$	VVVV	1/2	Y!
8	3744864	690	$U(4) \times Sp(2) \times O(2)$	VVV	1/2	Y!
9	3603236	466	$U(3) \times Sp(2) \times Sp(6) \times U(3)$	VVVV	1/2	Y
10	3308076	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
11	3308076	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
12	3091021	622	$U(6) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
13	2713960	460	$U(3) \times Sp(2) \times Sp(2) \times U(3)$	VVVV	1/2	Y!
14	2384626	560	$U(6) \times Sp(2) \times O(6)$	VVV	1/2	Y
15	2250118	668	$U(6) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!
16	1803909	519	$U(6) \times Sp(2) \times O(2)$	VVV	1/2	Y!
17	1787210	486	$U(4) \times Sp(2) \times U(3)$	VVV	1/2	Y
18	1787210	486	$U(4) \times Sp(2) \times U(3)$	VVV	1/2	Y
19	1674989	516	$U(8) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
20	1674416	384	$U(3) \times Sp(2) \times O(6) \times U(3)$	VVVV	1/2	Y
21	1641845	359	$U(3) \times Sp(2) \times Sp(6) \times U(5)$	VVVV	1/2	Y
22	1486664	346	$U(3) \times Sp(2) \times O(2) \times U(3)$	VVVV	1/2	Y!
23	1323363	476	$U(8) \times Sp(2) \times O(6)$	VVV	1/2	Y
24	1135044	349	$U(3) \times Sp(2) \times Sp(2) \times U(5)$	VVVV	1/2	Y!
25	1106616	209	$U(3) \times Sp(2) \times U(3) \times U(3)$	VVVV	1/2	Y
26	1106616	209	$U(3) \times Sp(2) \times U(3) \times U(3)$	VVVV	1/2	Y
27	1049176	531	$U(8) \times Sp(2) \times Sp(2)$	VVV	1/2	Y
28	956980	421	$U(8) \times Sp(2) \times O(2)$	VVV	1/2	Y
29	949189	448	$U(10) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
30	935034	351	$U(6) \times Sp(2) \times U(3)$	VVV	1/2	Y
31	935034	351	$U(6) \times Sp(2) \times U(3)$	VVV	1/2	Y
32	910132	51	$U(3) \times U(2) \times Sp(2) \times O(1)$	AAVV	0	Y

Curiosities

nr.	Total occ.	MIPFs	Chan-Paton group	Spectrum	x	Solved
161	115466	335	$U(4) \times U(2) \times U(2)$	VVV	1/2	Y
256	71328	167	$U(3) \times U(3) \times U(3)$	VVV	$\frac{1}{3}$	
561	23954	26	$U(3) \times U(2) \times U(1)$	AAS	1/2	Y!
562	23954	26	$U(3) \times U(2) \times U(1)$	AAS	0	Y!
708	16845	296	$U(5) \times O(1)$	AV	0	Y
1296	6432	87	$U(3) \times U(3) \times U(3)$	VVV	*	Y
1522	4753	115	$U(6) \times Sp(2)$	AV	1/2	Y!
1523	4753	115	$U(6) \times Sp(2)$	AV	0	Y!
2157	2381	115	$U(6) \times Sp(2)$	AV	1/2	Y!
2348	2062	34	$U(5) \times U(1)$	AS	1/2	Y!
2349	2062	34	$U(5) \times U(1)$	AS	0	Y!
8118	114	3	$U(3) \times Sp(2) \times U(1)$	AVS	1/2	
8305	108	1	$U(3) \times Sp(2) \times U(1)$	VVT	1/2	
12973	24	1	$U(3) \times U(3) \times U(3)$	VVV	1/2	
17042	6	1	$U(3) \times U(2) \times U(1)$	AVT	1/2	Y!
19345	1	1	$U(5) \times U(2) \times O(3)$	ATV	0	

Pati-Salam

4	4801518	867	$U(4) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!

```
Type:           U   S   S
Dimension       4   2   2
          5 x ( V  ,0  ,V  ) chirality -3
          3 x ( V  ,V  ,0  ) chirality 3
          2 x ( Ad,0  ,0  ) chirality 0
          2 x ( 0  ,A  ,0  ) chirality 0
          7 x ( 0  ,0  ,A  ) chirality 0
          4 x ( A  ,0  ,0  ) chirality 0
          2 x ( 0  ,S  ,0  ) chirality 0
          5 x ( 0  ,0  ,S  ) chirality 0
          7 x ( 0  ,V  ,V  ) chirality 0
```

Pati-Salam (2)

161	115466	335	$U(4) \times U(2) \times U(2)$	VVV	1/2	Y

```
Type:         U   U   U   U   U   S   U   O   U   O
Dimension     4   2   2   6   2   2   2   2   2   2
      4 x ( V  ,V  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 2
      1 x ( V  ,V*,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 1
      1 x ( V  ,0  ,V*,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality -1
      2 x ( V  ,0  ,V  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality -2
      2 x ( 0  ,V  ,V*,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality -2
      2 x ( V  ,0  ,0  ,0  ,V*,0  ,0  ,0  ,0  ,0  ) chirality 0
      4 x ( V  ,0  ,0  ,0  ,0  ,V  ,0  ,0  ,0  ,0  ) chirality 0
      2 x ( 0  ,S  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
      2 x ( A  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
      1 x ( Ad,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
      2 x ( V  ,0  ,0  ,0  ,V  ,0  ,0  ,0  ,0  ,0  ) chirality 0
      2 x ( 0  ,0  ,S  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
      4 x ( 0  ,V  ,0  ,0  ,0  ,0  ,V*,0  ,0  ,0  ) chirality 0
      2 x ( 0  ,V  ,0  ,0  ,0  ,0  ,V  ,0  ,0  ,0  ) chirality 0
      2 x ( 0  ,0  ,V  ,0  ,0  ,0  ,V*,0  ,0  ,0  ) chirality 0
      1 x ( 0  ,Ad,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
      2 x ( V  ,0  ,0  ,0  ,0  ,0  ,V*,0  ,0  ,0  ) chirality 0
      2 x ( V  ,0  ,0  ,0  ,0  ,0  ,V  ,0  ,0  ,0  ) chirality 0
      1 x ( 0  ,0  ,Ad,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
      2 x ( 0  ,V  ,0  ,0  ,0  ,0  ,0  ,0  ,V*,0  ) chirality 0
      2 x ( 0  ,0  ,V  ,0  ,0  ,0  ,0  ,0  ,V  ,0  ) chirality 0
```

Pati-Salam (2)

161	115466	335	$U(4)\times U(2)\times U(2)$	VVV	1/2	Y

```
Type:          U  U  U  U  U  S  U  O  U  O
Dimension      4  2  2  6  2  2  2  2  2  2
          4 x ( V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 2
          1 x ( V ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 1
          1 x ( V ,0 ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -1
          2 x ( V ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -2
          2 x ( 0 ,V ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -2
          2 x ( V ,0 ,0 ,0 ,V*,0 ,0 ,0 ,0 ,0 ) chirality 0
          4 x ( V ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ) chirality 0
          2 x ( 0 ,S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
          2 x ( A ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
          1 x ( Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
          2 x ( V ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ) chirality 0
          2 x ( 0 ,0 ,S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
          4 x ( 0 ,V ,0 ,0 ,0 ,0 ,V*,0 ,0 ,0 ) chirality 0
          2 x ( 0 ,V ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ) chirality 0
          2 x ( 0 ,0 ,V ,0 ,0 ,0 ,V*,0 ,0 ,0 ) chirality 0
          1 x ( 0 ,Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
          2 x ( V ,0 ,0 ,0 ,0 ,0 ,V*,0 ,0 ,0 ) chirality 0
          2 x ( V ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ) chirality 0
          1 x ( 0 ,0 ,Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
          2 x ( 0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,V*,0 ) chirality 0
          2 x ( 0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,V ,0 ) chirality 0
```

SU(5)

708	16845	296	$U(5) \times O(1)$	AV	0	Y

```
Type:           U   O   O
Dimension       5   1   1
          3 x  (A ,0 ,0 ) chirality 3
         11 x  (V ,V ,0 ) chirality -3
          8 x  (S ,0 ,0 ) chirality 0
          3 x  (Ad,0 ,0 ) chirality 0
          1 x  (0 ,A ,0 ) chirality 0
          3 x  (0 ,V ,V ) chirality 0
          8 x  (V ,0 ,V ) chirality 0
          2 x  (0 ,S ,0 ) chirality 0
          4 x  (0 ,0 ,S ) chirality 0
          4 x  (0 ,0 ,A ) chirality 0
```

Note: gauge group is just SU(5)!

Flipped SU(5)

2348	2062	34	$U(5) \times U(1)$		AS	1/2	Y!

```
Type:          U   U
Dimension      5   1
     11 x  (0 ,S ) chirality 3
      3 x  (A ,0 ) chirality 3
      5 x  (V ,V ) chirality -3
      8 x  (S ,0 ) chirality 0
      9 x  (Ad,0 ) chirality 0
      5 x  (0 ,Ad) chirality 0
      4 x  (0 ,A ) chirality 0
     12 x  (V ,V*) chirality 0
```

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

SU(5) x U(1)

2349	2062	34	$U(5) \times U(1)$	AS	0	Y!

```
Type:           U   U
Dimension       5   1
          11 x  (0 ,S ) chirality 3
           3 x  (A ,0 ) chirality 3
           5 x  (V ,V ) chirality -3
           8 x  (S ,0 ) chirality 0
           9 x  (Ad,0 ) chirality 0
           5 x  (0 ,Ad) chirality 0
           4 x  (0 ,A ) chirality 0
          12 x  (V ,V*) chirality 0
```

$$Y = -\frac{2}{3}Q_a + \frac{1}{2}Q_b$$

Trinification

1296	6432	87	$U(3) \times U(3) \times U(3)$	VVV	*	Y

```
        U   U   U   O   O   U   U   O   U   O
        3   3   3   4   2   6  12  12  12   4
3 x  (V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 3
3 x  (V ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
3 x  (0 ,V ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
1 x  (0 ,0 ,0 ,V ,0 ,V ,0 ,0 ,0 ,0 ) chirality -1
1 x  (0 ,0 ,0 ,0 ,0 ,S ,0 ,0 ,0 ,0 ) chirality 1
5 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,V ,0 ) chirality 1
3 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,S ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,0 ,A ,0 ,0 ,0 ,0 ) chirality -1
2 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,A ,0 ) chirality -2
1 x  (0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,V ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,V ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,0 ,V ,0 ,V ,0 ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,V ,0 ) chirality -1
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,V ,V ,0 ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,V ,0 ) chirality -1
1 x  (0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,V ) chirality -1
1 x  (0 ,0 ,0 ,V ,V ,0 ,0 ,0 ,0 ,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,S ,0 ,0 ,0 ,0 ,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,0 ,Ad,0 ,0 ,0 ,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,Ad,0 ,0 ,0 ) chirality 0
3 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,S ,0 ,0 ) chirality 0
3 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,Ad,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,S ) chirality 0
2 x  (0 ,0 ,0 ,0 ,V ,V ,0 ,0 ,0 ,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,V ,0 ,0 ,V ,0 ,0 ) chirality 0
2 x  (0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,V*,0 ) chirality 0
2 x  (0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,V*,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,V ) chirality 0
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,V ) chirality 0
```

Trinification

1296	6432	87	$U(3) \times U(3) \times U(3)$	VVV	*	Y

```
            U   U   U   O   O   U   U   O   U   O
            3   3   3   4   2   6  12  12  12   4
3 x  (V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 3
3 x  (V ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
3 x  (0 ,V ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
1 x  (0 ,0 ,0 ,V ,0 ,V ,0 ,0 ,0 ,0 ) chirality -1
1 x  (0 ,0 ,0 ,0 ,0 ,S ,0 ,0 ,0 ,0 ) chirality 1
5 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,V ,0 ) chirality 1
3 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,S ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,0 ,A ,0 ,0 ,0 ,0 ) chirality -1
2 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,A ,0 ) chirality -2
1 x  (0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,V ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,V ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,0 ,V ,0 ,V ,0 ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,V ,0 ) chirality -1
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,V ,V ,0 ,0 ) chirality 1
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,V ,0 ) chirality -1
1 x  (0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,V ) chirality -1
1 x  (0 ,0 ,0 ,V ,V ,0 ,0 ,0 ,0 ,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,S ,0 ,0 ,0 ,0 ,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,0 ,Ad,0 ,0 ,0 ,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,Ad,0 ,0 ,0 ) chirality 0
3 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,S ,0 ,0 ) chirality 0
3 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,Ad,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,S ) chirality 0
2 x  (0 ,0 ,0 ,0 ,V ,V ,0 ,0 ,0 ,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,V ,0 ,0 ,V ,0 ,0 ) chirality 0
2 x  (0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,V*,0 ) chirality 0
2 x  (0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,V*,0 ) chirality 0
1 x  (0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,V ) chirality 0
1 x  (0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,V ) chirality 0
```

Final Remarks

- It's just one small step:
  874 Hodge numbers scanned
  at least 30000 known (M. Kreuzer)
- Other quantitities of interest are computable in CFT (moduli couplings, Yukawa couplings)