One in a Billion: MSSM-like D-Brane Statistics

with Ralph Blumenhagen, Gabriele Honecker, Dieter Lüst and Timo Weigand

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Outline

1. Introduction
   - Motivation
   - Type II orientifold models
2. Methods of statistical analysis
   - Computer search
   - Number of solutions
3. Results
   - Full set of models
   - Searching for MSSM-like models
   - Results for Pati-Salam models
   - Statistics of the hidden sector
   - Gauge couplings
   - Correlations
4. Conclusions

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Motivation

- **Statistical approach** to string vacuum problem

  [Ashok, Denef, Douglas, Shiffman, Zelditch; De Wolfe, Giryavets, Kachru, Taylor, Tripathi; Misra, Nanda; Conlon, Quevedo; Kumar, Wells; Dine, Gorbatov, Thomas, O'Neil, Sun; Dienes, Dudas, Gherghetta; Acharya, Denef, Valandro]

- Analysis of the **gauge sector** in a specific setup
- **Distribution** of SM-like properties in these models
- **Correlations** between observables

General setup

- Type IIB orientifold flux compactifications
- Analysis of the $(\mathcal{N} = 1)$ gauge sector
- RR/NSNS 3-form fluxes to freeze complex structure moduli and dilaton
- Add magnetized D-branes to cancel tadpoles and get chiral fermions
- In the special class of orbifolds we are considering the consistency conditions are well under control

T-dual picture

Type IIA/$\Omega\overline{\sigma}$ with D6-branes at angles

- D-branes wrap sLag 3-cycles
- Symplectic basis: (α_I, β_I) of $H_3(M,\mathbb{Z})$, where $\alpha_I \in H_3^+(M)$ and $\beta_I \in H_3^-(M)$
- **O6-planes**:

$$\pi_{O6} = \frac{1}{2} \sum_{I=1}^{b_3/2} L_I \, \alpha_I$$

- **D6-branes**:

$$\begin{aligned} \pi_a &= \textstyle\sum_{I=1}^{b_3/2} (X_{a,I} \, \alpha_I + Y_{a,I} \, \beta_I), \\ \pi'_a &= \textstyle\sum_{I=1}^{b_3/2} (X_{a,I} \, \alpha_I - Y_{a,I} \, \beta_I) \end{aligned}$$

Consistency conditions

Tadpole concellation

$b_3/2 = 1 + h_{21}$ conditions:

$$\sum_{a=1}^{k} N_a \, X_{a,I} = L_I - L_{I,flux}$$

Supersymmetry conditions

- sLag condition: $\Im(\Omega_3)|_{\pi_a} = \sum_{I=1}^{b_3/2} Y_{a,I} \, F_I(U) = 0,$ where $F_I = \int_{\beta_I} \Omega_3$
- ~~anti-branes~~: $\Re(\Omega_3)|_{\pi_a} = \sum_{I=1}^{b_3/2} X_{a,I} \, U_I > 0$

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K-theory constraints

[Uranga; Marchesano, Shiu]

$$\sum_a N_a Y_{0,a} \in 2\mathbb{Z}$$

- Number of solutions changes by a factor of 6
- Models which have an odd rank of the gauge group are suppressed
  $\rightsquigarrow$ rank-distribution changes. $(rk = \sum_a N_a)$

Chiral matter

We get chiral matter at the **intersection** of D-branes

$$\begin{aligned} I_{ab} &= \pi_a \circ \pi_b \\ &= \sum_I X_{a,I}\, Y_{b,I} - Y_{a,I}\, X_{b,I} \end{aligned}$$

$\rightsquigarrow$ I_{ab} chiral multiplets in a bifundamental $U(N_a) \times U(N_b)$ representation.

Specific setup

Orbifold: $T^2 \times T^2 \times T^2/\mathbb{Z}_2 \times \mathbb{Z}_2$ [Cvetic, Shiu, Uranga]

- $(h_{1,1}, h_{2,1}) = (51, 3)$
- Wrapping numbers $(n_I, m_I), I \in \{1, 2, 3\}$
- Tilted tori: $m_I \rightarrow m_I + b_I n_I, \quad b_I \in \{1/2, 1\}$
- Define

$$X_0 = n_1\, n_2\, n_3\,,\;\; X_1 = -n_1\, m_2\, m_3\,,\;\; X_2 = -m_1\, n_2\, m_3\,,\;\; X_3 = -m_1\, m_2\, n_3\,,$$
$$Y_0 = m_1\, m_2\, m_3\,,\;\; Y_1 = -m_1\, n_2\, n_3\,,\;\; Y_2 = -n_1\, m_2\, n_3\,,\;\; Y_3 = -n_1\, n_2\, m_3\,,$$

satisfying

$$X_I\, Y_I = X_J\, Y_J\ \forall\ I, J, \quad X_I\, X_J = -Y_K\, Y_L\,,$$
$$X_L\, (Y_L)^2 = -X_I\, X_J\, X_K\,, \quad Y_L\, (X_L)^2 = -Y_I\, Y_J\, Y_K \quad I, J, K \text{cyclic}$$

Constraints from consistency conditions

- SUSY:

$$\sum_{I=0}^{3} Y_I U_I^{-1} = 0, \quad \text{ans} \quad \sum_{I=0}^{3} X_I U_I > 0,$$

- Tadpole cancellation:

$$\sum_a N_a X_{a,I} = L_I, \qquad I \in \{0..4\},$$

- Combined:

$$0 < \sum_{I=0}^{3} X_I U_I \leq \sum_{I=0}^{3} L_I U_I$$

In our models: $L_0 = 8 - N_{flux}; \quad L_i = 8, \quad i \in \{1,2,3\}.$
$\rightsquigarrow$ SUSY restricts the amount of admissable 3-form flux.

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Problem

Find solutions of diophantine equations of the form

$$\sum_{a=1}^{k} N_a \, X_a^I = L^I$$

Solution

1. Choose values for U_I. Generate sets of X^I that fulfill SUSY conditions.
2. Count number of partitions $\sum_{a=1}^{k} S_a = L^I U_I$.
3. Factorize $S_a = N_a (X_a^I U_I)$ using values for the X_a from step 1.
4. Check if tadpole and K-theory conditions are fulfilled.

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Computer search

Performed using a fast partition/factorization algorithm for natural numbers.

- With the help of a computer cluster ($>$ 500 processors running for $\approx$ 6 months) all possible solutions (for a sufficient range of U_I) have been generated

  $\rightsquigarrow$ almost complete classification of models on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$.

- In total $\sim 10^8$ models have been analysed

Counting solutions

- Susy and tadpole conditions allow only for three sets of X_I: Only stacks with 1, 2, or 4 non-vanishing X_I are possible.
- In the first two cases one can prove that the number of solutions is finite.
- In the last case we get $X_A = -\left(\sum_i \frac{U_A}{U_i X_i}\right)^{-1}$.
  $\rightsquigarrow$ for a sufficient number of these branes the complex structures are fixed at rational values

$$1 \leq X_i \leq \sum_{P=0}^{3} \frac{u_{P,2} u_{Q,1} u_{R,1} u_{S,1} L_P}{u_{i,2} u_{J,1} u_{K,1} u_{L,1}}$$

  $\rightsquigarrow$ for fixed complex structures only a finite number of branes are admissible
- **Computer analysis:** number of solutions decreases rapidly for high values of the complex structures

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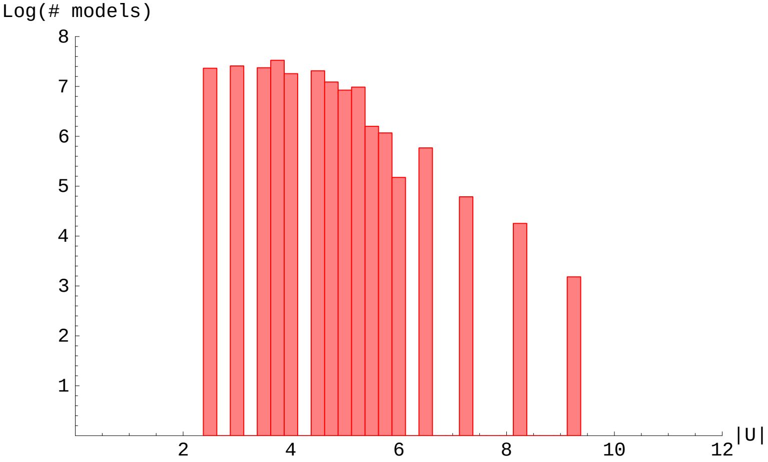

Number of models computed depending on the absolute value of our complex structure variables.

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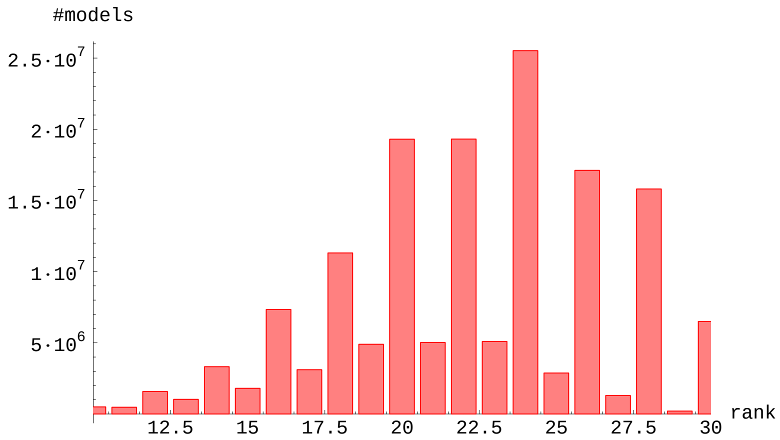
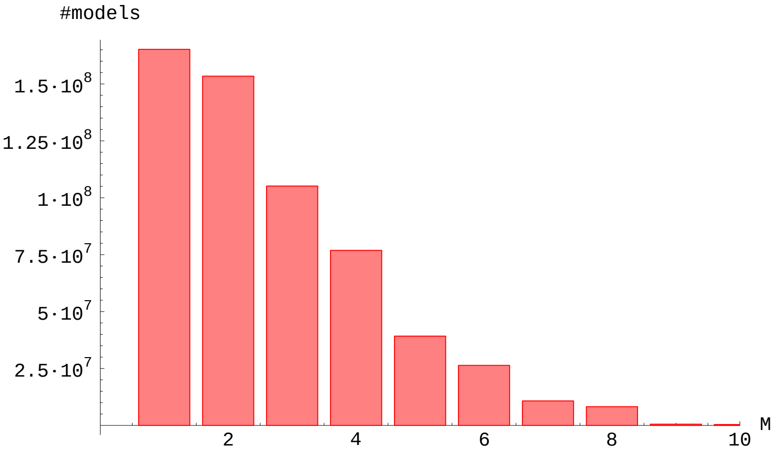
Total rank distribution



Distribution of U(M) gauge groups



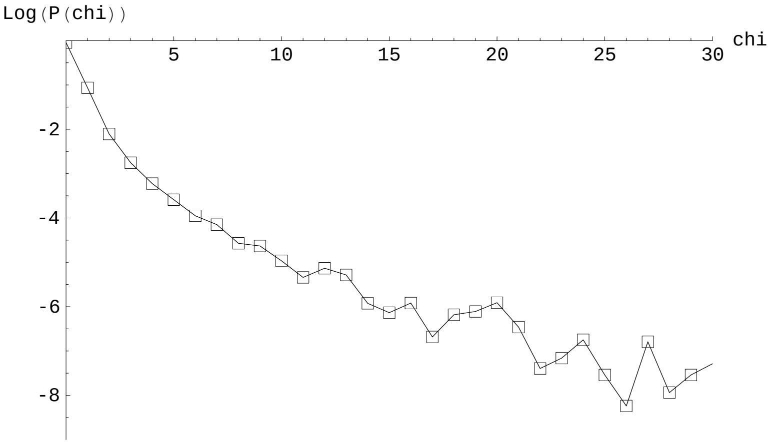
Chirality

- As a measure for overall **chirality** we consider

$$\chi = \sum_{a>b} I_{a',b} - I_{a,b} = 2\,\vec{Y}_a \vec{X}_b$$

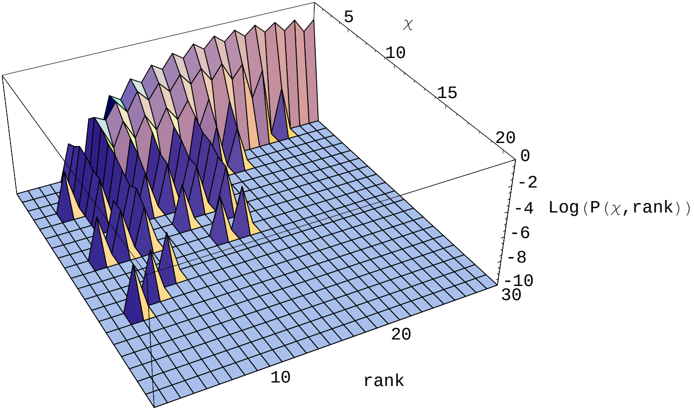
- **Odd** values for χ are possible only from tilted tori.

Chirality distribution



Logarithmic plot of frequencies of given mean chirality.

Rank vs chirality



Distribution of models with fixed rank and chirality.

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Aim: Systematic investigation of distribution of vacua with standard model-like characteristics among set of SUSY solutions. $\rightsquigarrow$ MSSM realized on 4 or 3 stacks of branes

- **4 stacks:** $U(3)_a \times U(2)_b / Sp(2)_b \times U(1)_c \times U(1)_d$

  QCD $U(3)_a = SU(3)_{QCD} \times U(1)_a$
  weak $U(2)_b = SU(2)_w \times U(1)_b$
  $U(1)_Y$: appropriate (massless) combination $Q_Y = \sum x_i Q_i$

- **3 stacks:** possible if $x_c = x_d$ by dropping stack d in 4 stack solution

MSSM realizations

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Additional constraints

We want a **chiral spectrum** on intersections of MSSM branes

$$\begin{aligned} \#(N_a, \overline{N_b}) &= \pi_a \circ \pi_b \\ \#\mathsf{Anti}_a &= \frac{1}{2}(\pi_a \circ \pi_{a'} + \pi_a \circ \pi_{O6}) \\ \#\mathsf{Sym}_a &= \frac{1}{2}(\pi_a \circ \pi_{a'} - \pi_a \circ \pi_{O6}) \end{aligned}$$

$\rightsquigarrow$ systematic realization of MSSM quantum numbers

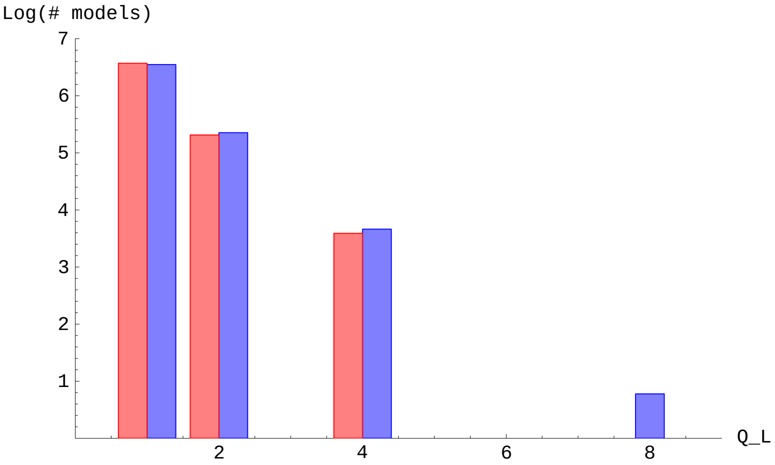
Anomaly considerations

- Freedom of non-abelian anomalies guaranteed by RR-tadpole cancellation
- $U(1)_a - SU(N_b)^2$ mixed anomalies cancelled by GS mechanism, but have to make sure that specific realization of $U(1)_Y = \sum x_i U(1)_i$ is anomaly free and does not receive mass by GS-coupling, i.e.

$$\sum_a x_a N_a Y_I^a = 0, \quad I = 0, \ldots, 3$$

- **No** MSSM configurations with **three** generations and massless $U(1)$ have been found in the analysed data.
- **Reason:** All known solutions work with values for the complex structure which is outside the range we considered. [Cvetic et al.; Marchesano, Shiu]
- $\rightsquigarrow$These models are statistically **highly suppressed**.

Distribution of generations



Number of models found for MSSM configurations (red), allowing for a massive $U(1)$ (blue).

Pati-Salam models

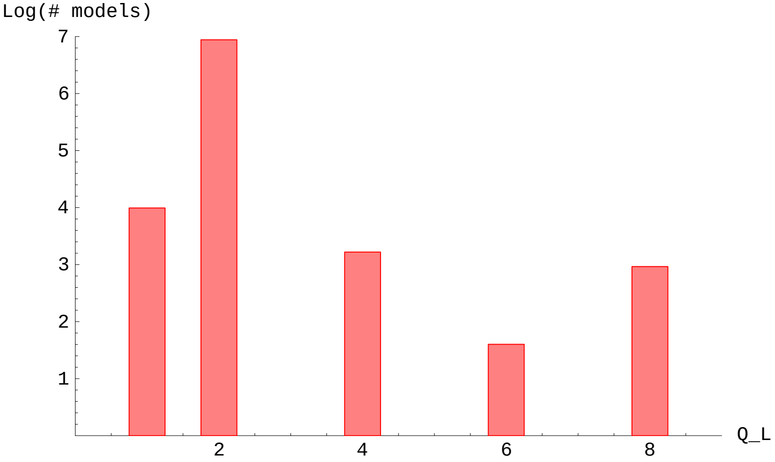
In addition we consider possible Pati-Salam models with gauge group

$$SU(4) \times SU(2)_L \times SU(2)_R$$

[see e.g. Cvetic et al.]

- **Condition:** Intersection numbers between SU(4) and both SU(2) stacks have to be equal
- **Number of generations:** We did **not** see **three** generation models (for the same reason as in the MSSM case)

Distribution of generations



Number of models found for Pati-Salam configurations.

Hidden sector

Besides the standard model or Pati-Salam gauge group we have in general a hidden sector

$$G = G_{SM} \oplus H.$$

Question

Are the distributions in the hidden sector different from the distributions in the full set of models?

Answer

No, they are not. The distribution of gauge group factors or chirality in the hidden sector of standard model or Pati-Salam configurations is basically the same as in the full set of models.

$\rightsquigarrow$ Some properties of our models might be **generic** in the sense that they do not depend on the constraints for the visible sector.

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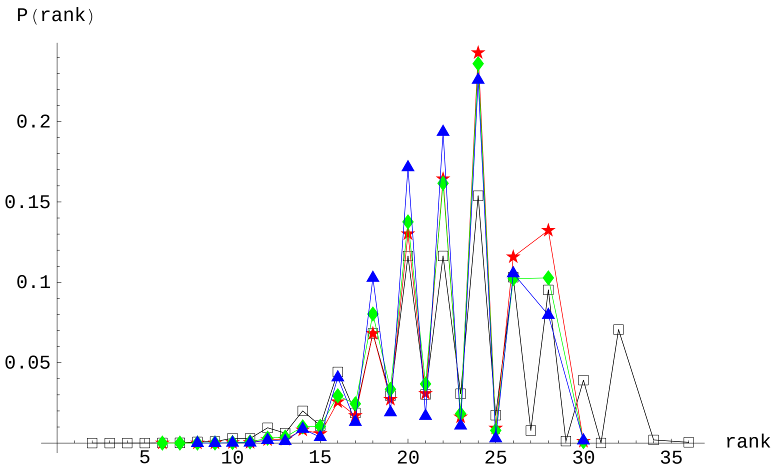
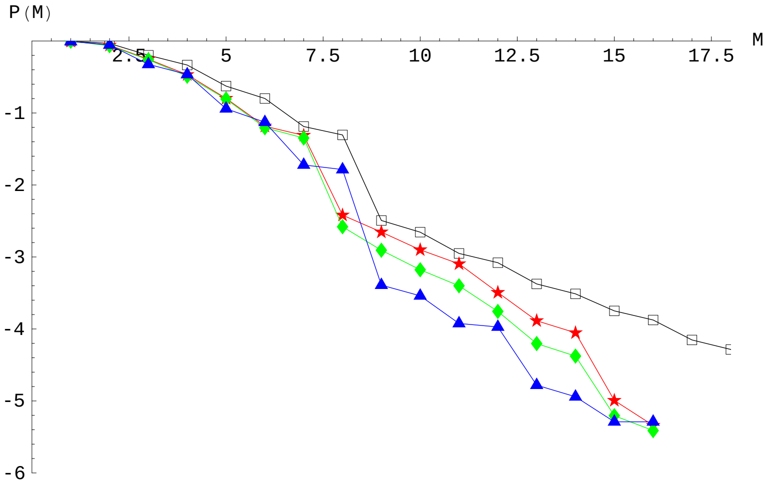
Rank distribution in the hidden sector



Black boxes: All models, red stars: MSSM (massless $U(1)$), green diamonds: MSSM (all $U(1)$), blue triangles: Pati-Salam.

$U(M)$ distribution in the hidden sector



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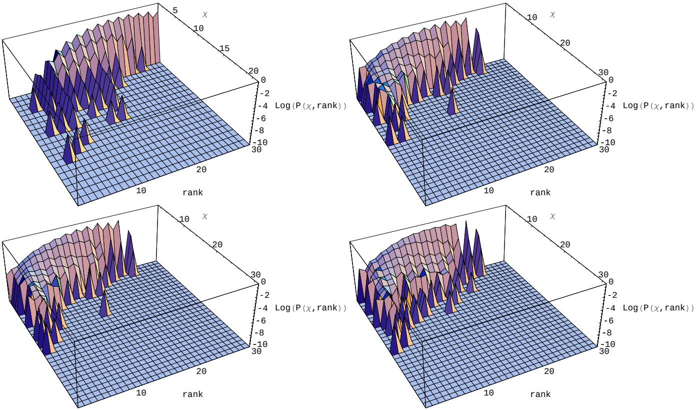
Rank vs Chirality



Form top-left to bottom-right: All models, MSSM-like, massive MSSM, Pati-Salam.

Gauge couplings

So far we considered properties of the models which are topological, in the sense that they depend on the brane configuration only. A geometric quantity one might consider are the **gauge couplings** α_s, α_w and α_Y.

In principle they should be considered at **low energy**, but this would imply that we use the renormalization group to evolve them down from their values at the **string scale**.

$\rightsquigarrow$ We do not do this, but consider their string-scale values just to get some hints about their behaviour.

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Calculation of the gauge couplings

$$\frac{1}{\alpha_a} = \frac{c}{\kappa_a} \frac{1}{\hat{b}\sqrt{\prod_{i=1}^{3} R_1^{(i)} R_2^{(i)}}} \sum_{I=0}^{3} \hat{X}^I U_I,$$

with some normalization constant $c = \frac{1}{2\sqrt{2}} \frac{M_{Planck}}{M_s}$ and $\kappa_a \in \{1, 2\}$, depending if we have a $U(N)$ or $SO(N)$ stack.
Note: Explicit dependence on the complex structure.

Conjecture about relations

There exists a conjecture that (most) intersecting brane models should obey the relation [Blumenhagen, Stieberger, Lüst]

$$\frac{1}{\alpha_Y} = \frac{2}{3} \frac{1}{\alpha_s} + \frac{1}{\alpha_w}.$$

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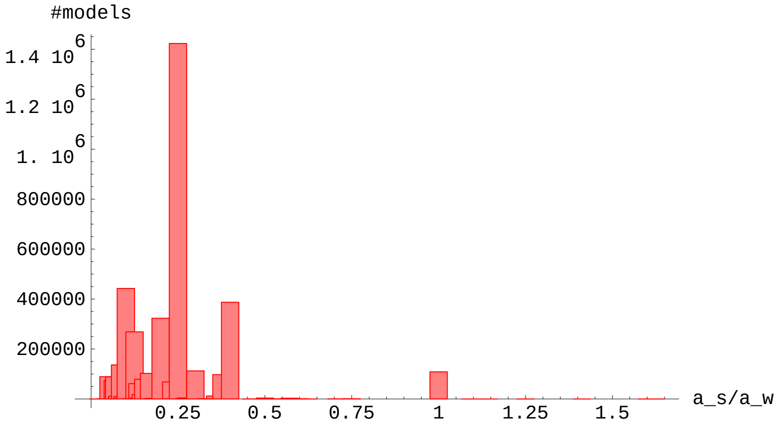
Distribution of α_s/α_w



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The Weinberg angle $\sin^2\theta$ is given by

$$\sin^2\theta = \frac{\alpha_Y}{\alpha_w + \alpha_Y}.$$

If the conjectured relation between the coupling constants is correct we would have the following relation between $\sin^2\theta$ and α_s/α_w

$$\sin^2\theta = \frac{3}{2}\frac{1}{\alpha_w/\alpha_s + 3}.$$

Result

88% of all models fulfill this relation.

$sin^2\theta$

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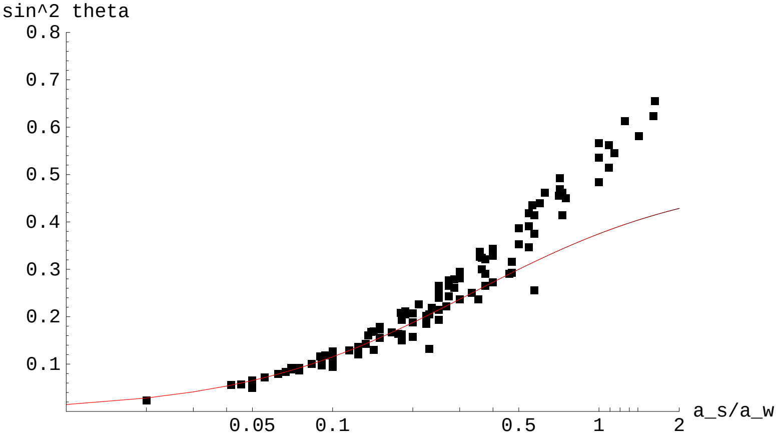
Values for $\sin^2\theta$



Logarithmic plot of α_s/α_w against $sin^2\theta$. Each dot represents a class of models with the same values.

The conjectured relation is shown as a red curve.

Correlations

Question

Are the atomic properties of the models (like existence of certain gauge groups, total rank, chirality, etc.) **correlated**?

Answer

Yes, some of them are, **but** only **global** properties, for example the mean chirality and the total rank of the gauge group.

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Correlations between different constraining properties are **very small**. If this is true, it would be possible to make predictions about the probability to find models with specific properties without constructing them.

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Calculate correlation between different properties

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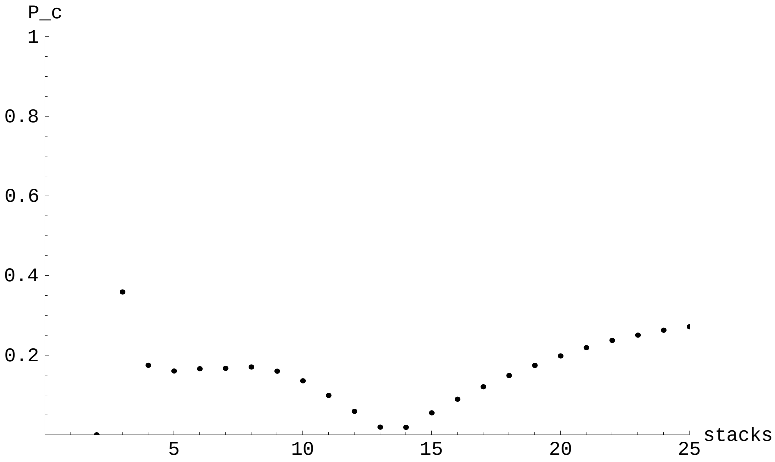

Correlations between the existence of $U(3)$ and $U(2)/Sp(2)$ gauge groups.

Estimate of three generation MSSMs

Using this we can try to estimate the number of standard models with three generations in the complete setup, although we have not explicitly constructed a single one.

Restriction	Factor
gauge factor $U(3)$	0.0816
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No symmetric representations	0.839
Massless $U(1)_Y$	0.423
Three generations of quarks	2.92×10^{-5}
Three generations of leptons	1.62×10^{-3}
Total	1.3×10^{-9}

(matches with Gepner model constructions from Schellekens et.al.)

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Compare with estimates done in the same way for models with 2 or 4 generations, where we have exact results.

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- Motivation
- Type II orientifold models

2 Methods of statistical analysis
- Computer search
- Number of solutions

3 Results
- Full set of models
- Searching for MSSM-like models
- Results for Pati-Salam models
- Statistics of the hidden sector
- Gauge couplings
- Correlations

4 Conclusions

Summary

- Standard model configurations are heavily suppressed from a statistical point of view.
- There exist non-trivial overall statistical correlations between physical observables.
- The constraining properties of realistic models are quite uncorrelated.
  $\rightsquigarrow$ features of distributions of sm-properties can be estimated without explicit calculation.

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Thank you!