From Heterotic String Theory to the Supersymmetric Standard Model

Hans Peter Nilles

Physikalisches Institut

Universität Bonn

Outline

- Heterotic braneworld
- Localization of matter and gauge fields
- A benchmark model
- Gauge-Yukawa Unification
- See-Saw and R-parity as SO(10) remnants
- The μ problem
- Discrete symmetries a a source for accidental U(1) symmetries
- Hierarchies from accidental R-symmetries
- Accions
- Outlook

The heterotic braneworld

Quarks, Leptons and Higgs fields can be localized:

- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

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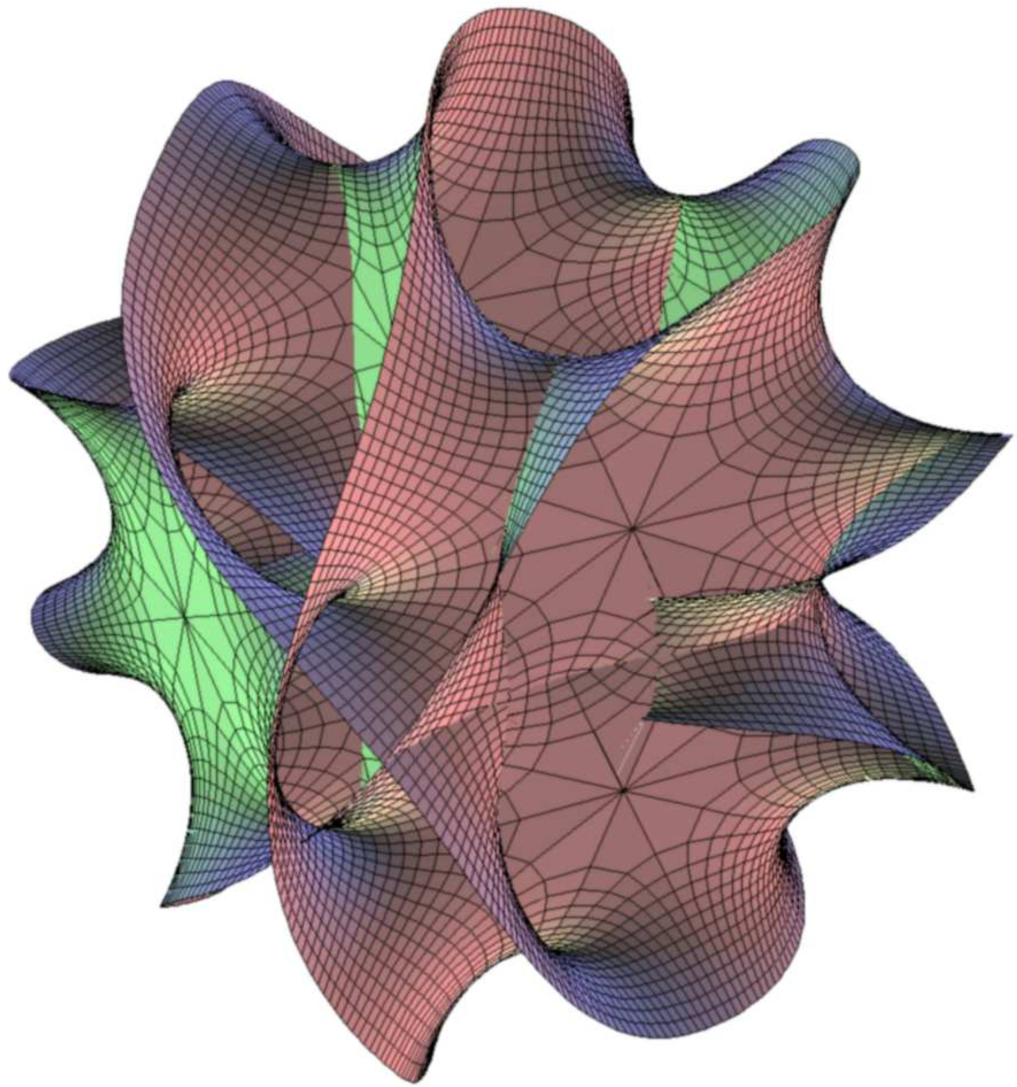
but there is also a “localization” of gauge fields

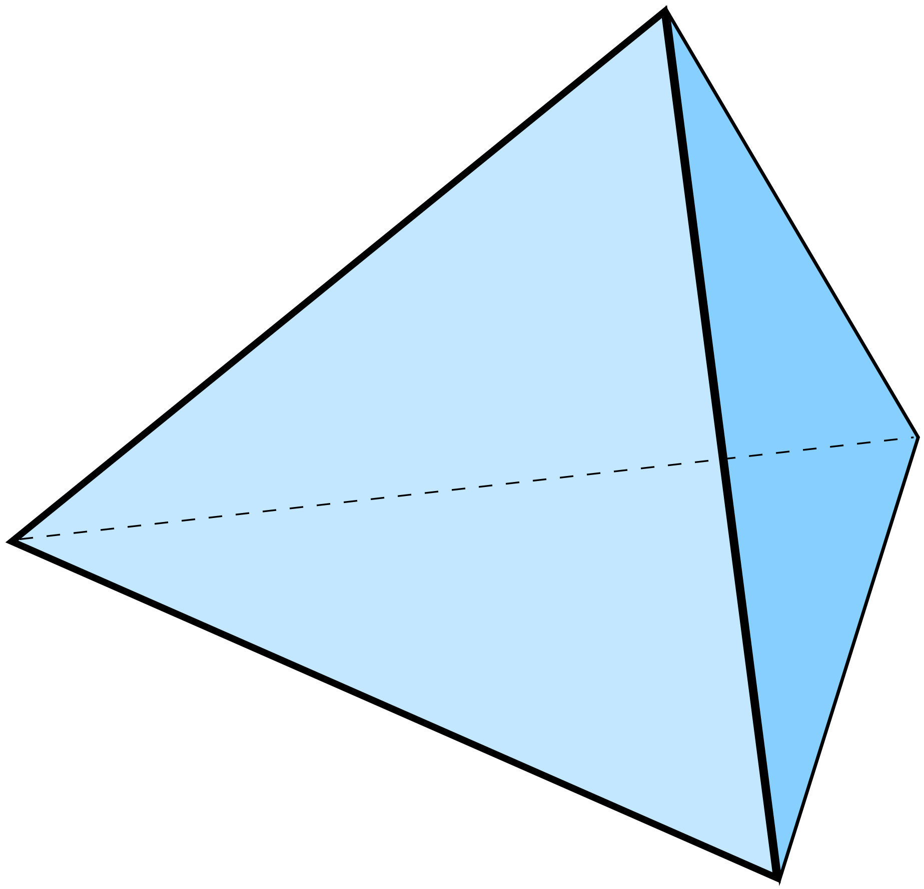
- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

Observed 4-dimensional gauge group is common subroup of the various localized gauge groups!

Calabi Yau Manifold

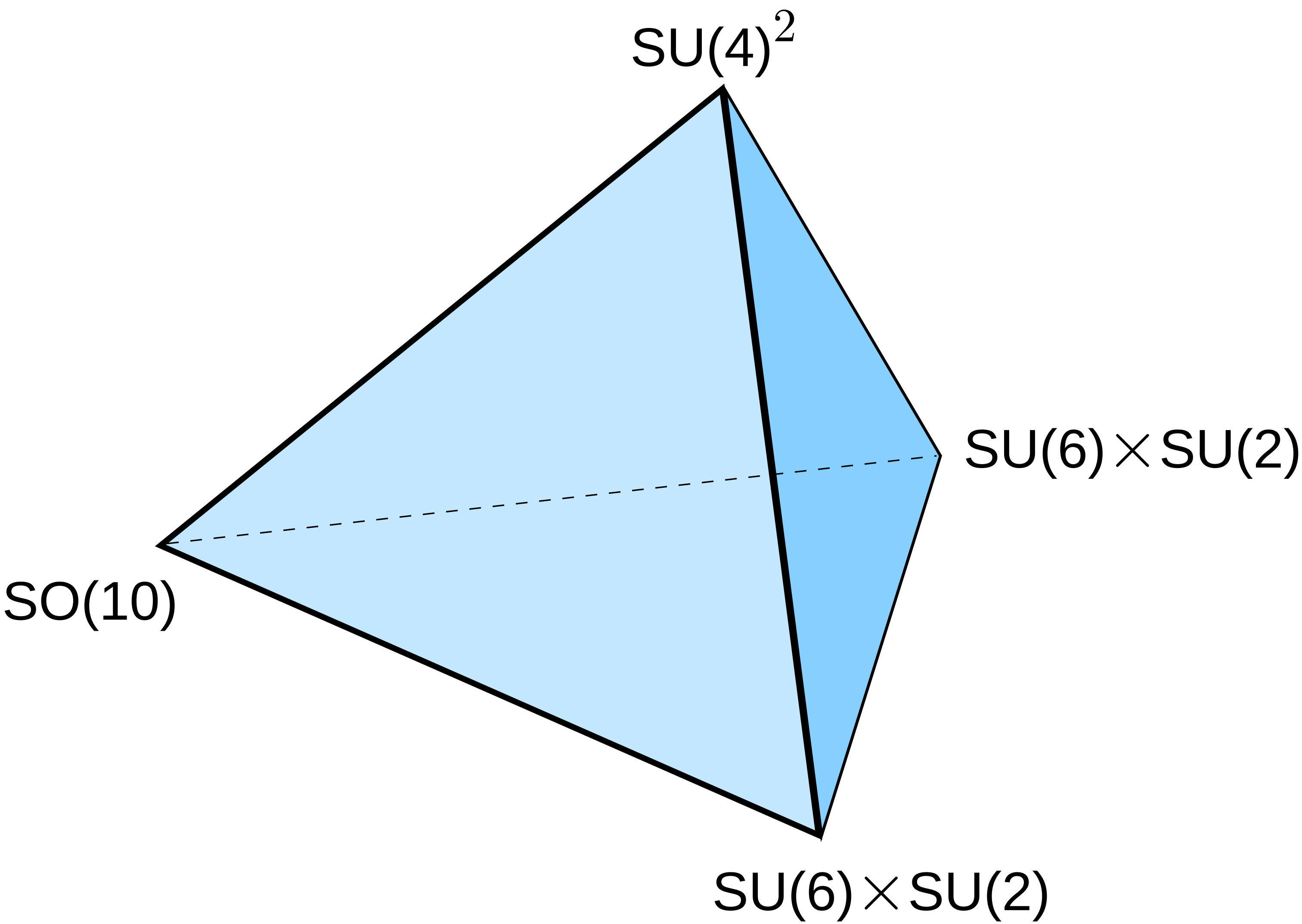


Orbifold



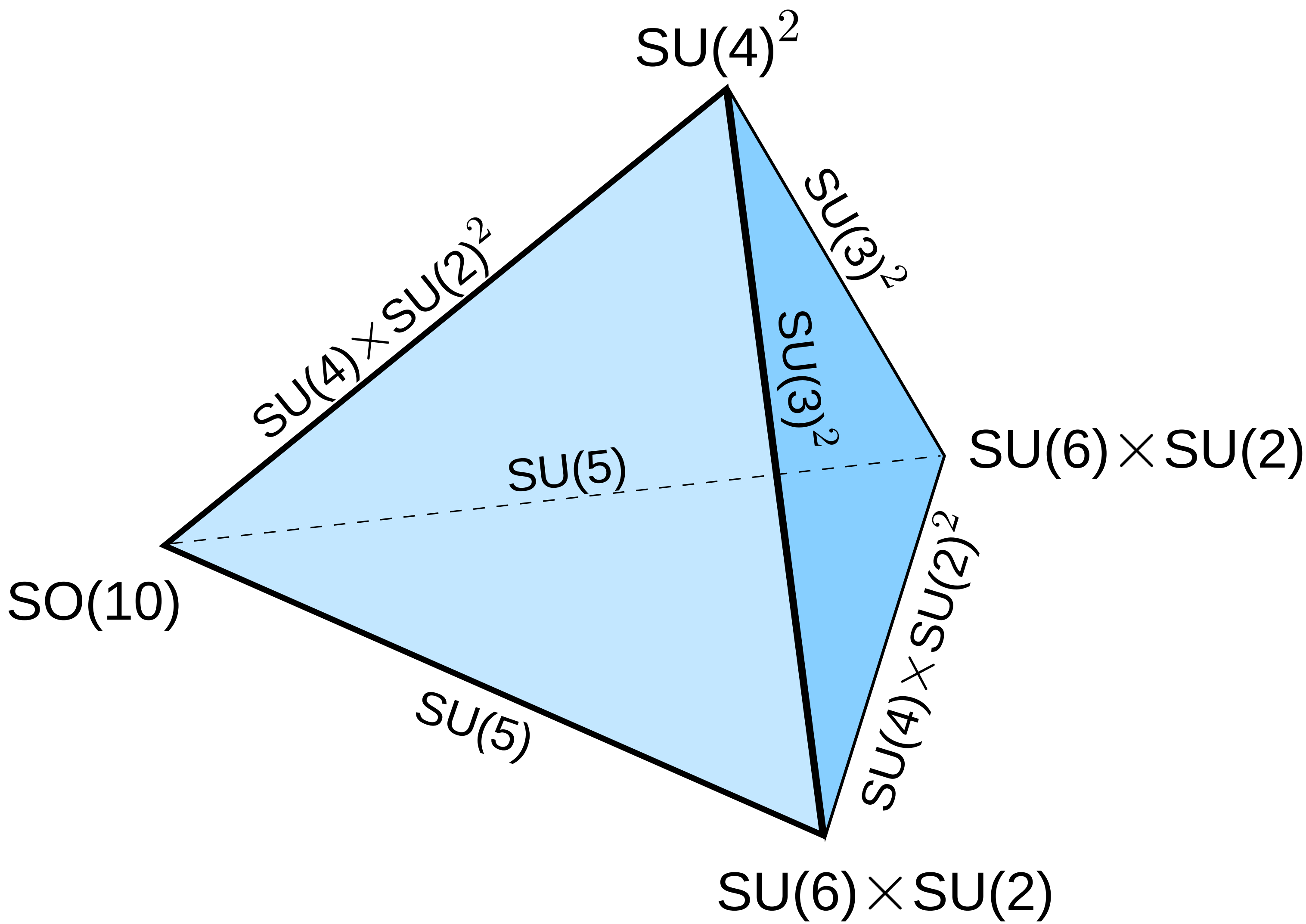
(Förste, HPN, Vaudrevange, Wingerter, 2004)

Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Local Grand Unification

In fact (heterotic) string theory gives us a variant of GUTs

- complete multiplets for fermion families
- split multiplets for gauge- and Higgs-bosons
- partial Yukawa unification

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Key properties of the theory depend on the geography of the fields in extra dimensions.

This geometrical set-up called local GUTs, can be realized in the framework of the “heterotic braneworld”.

(Förste, HPN, Vaudrevange, Wingerter, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

The road to the MSSM

This scenario (up to now) leads to

- few hundred explicit globally consistent models with the exact spectrum of the MSSM (absence of chiral exotics)
- local grand unification (by construction)
- gauge- and (partial) Yukawa unification
- examples of neutrino see-saw mechanism
- models with R-parity
- hidden sector gaugino condensation
- discrete symmetries

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006-2008)

Discrete Symmetries

There are numerous discrete symmetries

- from geometry
- and from stringy selection rules

(Kobayashi, HPN, Plöger, Raby, Ratz, 2006)

Possible applications:

- family symmetries (for the flavor problem)
- Yukawa textures
- creation of hierarchy

(Kappl, HPN, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange, 2008)

- approximate global $U(1)$ for a QCD axion

(Choi, HPN, Ramos-Sanchez, Vaudrevange, 2009)

A Benchmark Model

At the orbifold point the gauge group is

$$SU(3) \times SU(2) \times U(1)^9 \times SU(4) \times SU(2)$$

- one $U(1)$ is anomalous
- there are singlets and vector-like exotics
- decoupling of exotics and breakdown of gauge group has been verified
- remaining gauge group

$$SU(3) \times SU(2) \times U(1)_Y \times SU(4)_{\text{hidden}}$$

- for discussion of neutrinos and R-parity we keep also the $U(1)_{B-L}$ charges

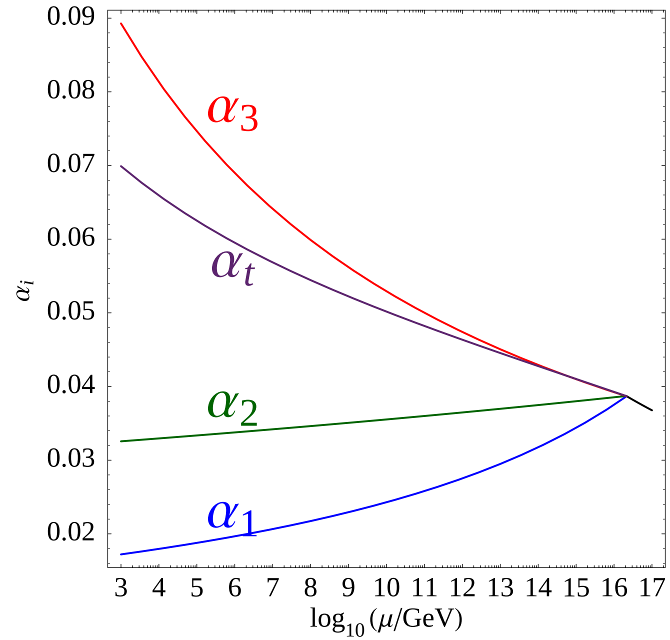
Spectrum

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$		8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	h_d		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	h_u
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$		6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$	s_i^+		14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/2,*)}$	s_i^-
16	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$	$\bar{n}_i$		13	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,-1)}$	n_i
5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,1)}$	$\bar{\eta}_i$		5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,-1)}$	η_i
10	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,0)}$	h_i		2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{(0,0)}$	y_i
6	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(0,*)}$	f_i		6	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(0,*)}$	$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
4	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,\pm 2)}$	χ_i		32	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,0)}$	s_i^0
2	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

Unification

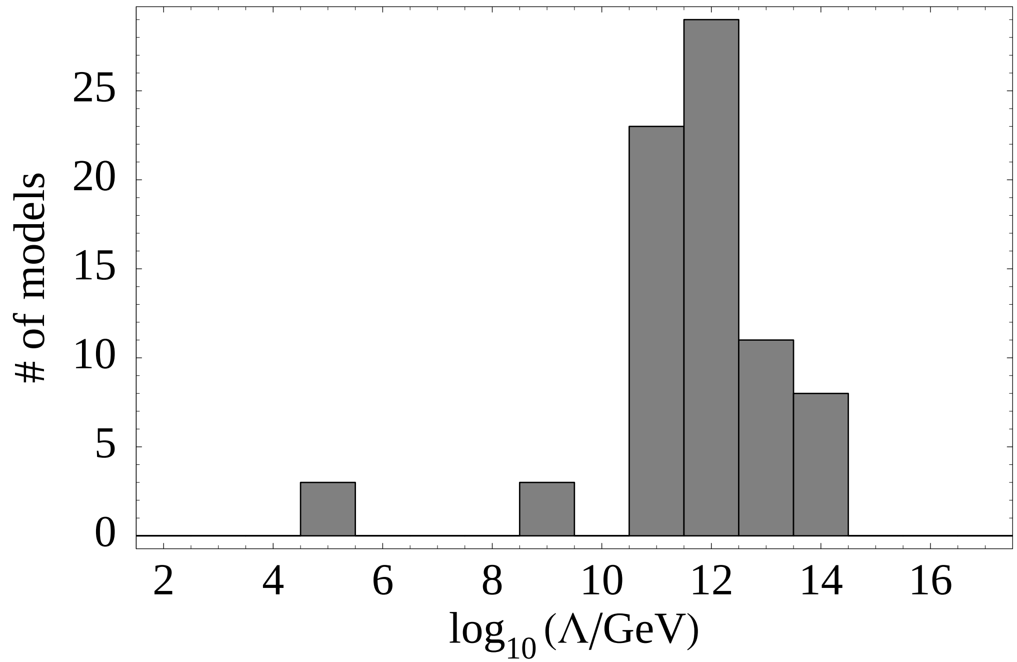
- Higgs doublets are in untwisted (U3) sector

- trilinear coupling to the top-quark allowed ($m_{\text{top}} \sim 172$ GeV)



- threshold corrections (“on third torus”) allow unification at correct scale around 10^{16} GeV

Hidden Sector Susy Breakdown



Gravitino mass $m_{3/2} = \Lambda^3/M^2_{\text{Planck}}$ is in the TeV range for the hidden sector gauge group $SU(4)$

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006)

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The μ problem

In general we have to worry about

- doublet-triplet splitting
- mass term for additional doublets
- the appearance of “naturally” light doublets

In the benchmark model we find

- only 2 doublets
- which are neutral under all selection rules
- if $M(s_i)$ allowed in superpotential
- then $M(s_i)H_uH_d$ is allowed as well

The μ problem II

We have verified that (up to order 6 in the singlets)

- $F_i = 0$ implies automatically
- $M(s_i) = 0$ for all allowed terms $M(s_i)$ in the superpotential W

Therefore

- $W = 0$ in the supersymmetric (Minkowski) vacuum
- as well as $\mu = \partial^2 W/\partial H_u \partial H_d = 0$, while all the vectorlike exotics decouple
- broken susy then implies $\mu \sim m_{3/2} \sim < W >$

This solves the μ-problem

The creation of the hierarchy

Is there an explanation for a vanishing μ?

- string miracle?
- underlying symmetry?

Consider a superpotential

$$W \;=\; \sum c_{n_1\cdots n_M}\phi_1^{n_1}\cdots\phi_M^{n_M}\;.$$

with an exact R-symmetry

$$W \;\to\; e^{2\mathrm{i}\,\alpha}\,W\;,\quad \phi_j\;\to\;\phi_j'\;=\;e^{\mathrm{i}\,r_j\,\alpha}\,\phi_j$$

where each monomial in W has total R-charge 2.

...hierarchy continued...

Consider a field configuration $\langle \phi_i \rangle$ with

$$F_i \;=\; \frac{\partial W}{\partial \phi_i} \;=\; 0 \quad \text{at } \phi_j = \langle \phi_j \rangle \; \forall \; i, j \; .$$

Under an infinitesimal $U(1)_R$ transformation, the superpotential transforms nontrivially

$$W(\phi_j) \;\to\; W(\phi_j') \;=\; W(\phi_j) + \sum_i \frac{\partial W}{\partial \phi_i} \Delta \phi_i \; .$$

This proves that, if the $F = 0$ equations are satisfied, W vanishes at the minimum (as a consequence of a continuous R-symmetry)

Continuous R-symmetry

Thus for a continous R-symmetry we would have

- a supersymmetric ground state with $W = 0$ and $\mathrm{U}(1)_R$ spontaneously broken
- a problematic R-Goldstone-Boson

However, the above R-symmetry appears as an accidental continous symmetry resulting from an exact discrete symmetry of (high) order N

- Goldstone-Boson massive and harmless
- a nontrivial VEV of W of higher order in ϕ

(Kappl, HPN, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange, 2008)

Hierarchy

Such accidental symmetries lead to

- creation of a small constant in the superpotential
- explanation of a small μ term

(Kappl, HPN, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange, 2008)

Even with a moderate hierarchy like $\phi/M_P \sim 10^{-2}$ one can generate small values for μ and $< W >$ and thus a hierarchically small TeV-scale for the gravitino mass

$$m_{3/2} \sim W_{\text{eff}} = c + A\,\mathrm{e}^{-a\,S}$$

in the framework of a modulus or mirage mediation scheme of supersymmetry breakdown.

(Löwen, HPN,2008)

Accions

Absence of continuous global U(1) symmetries in string theory leads to a question towards the

- axion as a solution to the strong CP-problem

A gauge anomalous $U(1)$ symmetry might help, but there we expect

- a too large axion decay constant of order of string scale

Again additional accidental gobal U(1) symmetries arising as a consequence of discrete symmetries might help,

(Choi, Kim, Kim, 2007; Choi, HPN, Ramos-Sanchez, Vaudrevange, 2009)

but we need to control the accion scale F_a.

Multi-Axion Systems

Consider a system with two $U(1)$ symmetries: $U(1)_P \times U(1)_Q$ and suppose that they are broken spontaneously.

$$F_{a_1} \;=\; -\, v_1 \,\frac{q_P^1\, q_Q^2 - q_Q^1\, q_P^2}{q_f^2}\,, \qquad F_{a_2} \;=\; v_2 \,\frac{q_P^1\, q_Q^2 - q_Q^1\, q_P^2}{q_f^1}\,.$$

The relevant accion decay constant will then be

$$F_a = \left(\left(\frac{1}{F_{a_1}}\right)^2 + \left(\frac{1}{F_{a_2}}\right)^2 \right)^{-1/2} \;=\; \frac{v_1\, v_2\, (q_P^1\, q_Q^2 - q_Q^1\, q_P^2)}{\sqrt{(q_f^1\, v_1)^2 + (q_f^2\, v_2)^2}}\,.$$

and it is dominated by the smallest VEV!

The Accion Program

- find a model with an accidental (colour)-anomalous $U(1)^*$
- identify a vacuum configuration where the VEVs driven by the Fayet-Iliopoulos term do not break $U(1)^*$
- search for a vacuum configuration where $U(1)^*$ is broken by a VEV in the axion window (some other gauge $U(1)$'s might be broken here as well)
- check that higher order non-renormalizable terms that break $U(1)^*$ explicitely are sufficiently suppressed to avoid a too “large” axion mass.

(Choi, HPN, Ramos-Sanchez, Vaudrevange, 2009)

can be accomodated in the Heterotic Brane World.

Conclusions

Heterotic braneworld with local grand unification leads to

- gauge-Yukawa unification ($m_{\rm top} \sim 172$ GeV)
- See-Saw and R-parity as SO(10) remnants
- a solution to the μ problem

Discrete symmetries play a fundamental role

- family symmetries avoid the flavor problem in gravity mediation
- Yukawa textures for quark and lepton masses
- R-Parity and the question of proton stability

Conclusions II

Discrete symmetries lead to accidental global U(1) symmetries:

- accidental R-symmetries and the μ-term
- a small VEV of the superpotential (gravitino mass)
- accions as a solution to the strong CP problem
- accion decay constant in the axion window

This shows that the properties of the model depend strongly on the geography of the extra dimensions with localized matter and gauge fields.

We seem to live at (or close to) a very special point in moduli space!