The ZIP Code of MSSM Particles

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Where do MSSM fields live?

Localization properties of quarks, leptons and Higgses

- Higgs bosons and top-quark in the “bulk” lead to large top-quark Yukawa coupling
- first 2 families localized (exhibiting family symmetries)

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The legacy of higher dimensions

- Mirage Mediation (compressed spectrum for gauginos)
- Natural Susy
- discrete (nonabelian) family symmetries

Remnants of N=4 SUSY from higher dimensions that might hide Susy at the LHC!

Guidelines

- Spinors if SO(10) might be important even in absence of GUT gauge group
- gauge-top Yukawa unification in the MSSM
- presence of discrete symmetries with many applications

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

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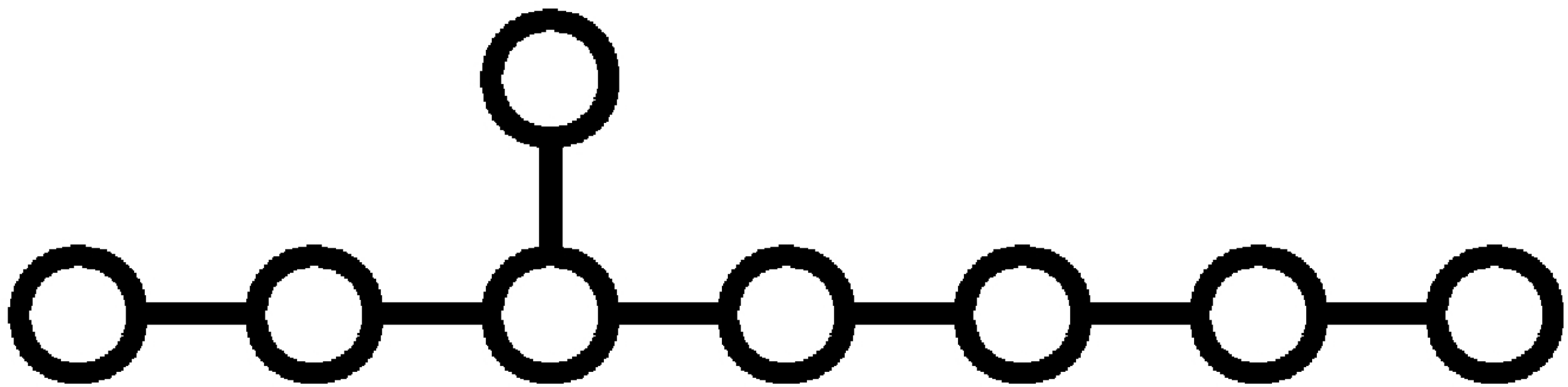
From the mathematical structure we might prefer exceptional groups

- There is a maximal group: E_8,
- but E_8 and E_7 do not allow chiral fermions in $d = 4$.
- How does this fit with our usual picture of unification based on SU(5) or SO(10)?

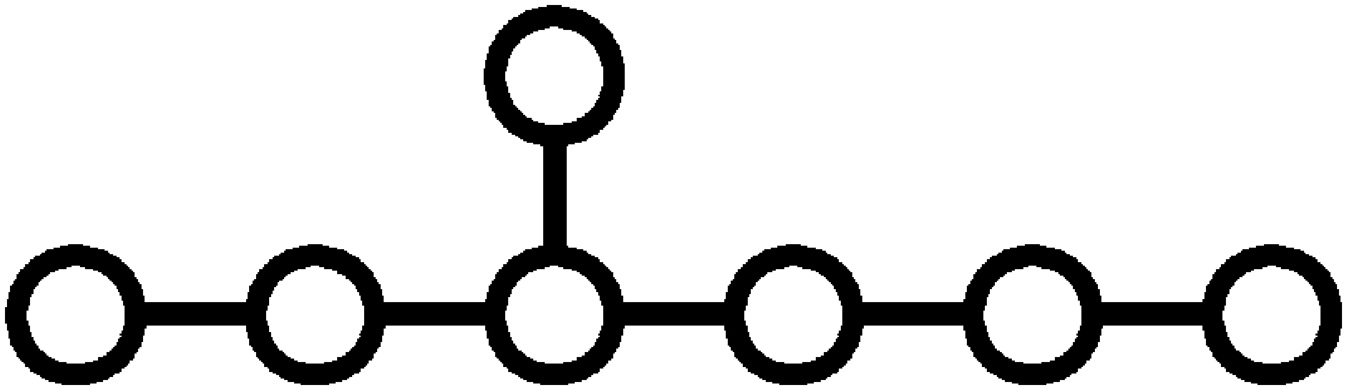
Maximal Group



E_8 is the maximal group.

There are, however, no chiral representations in $d = 4$.

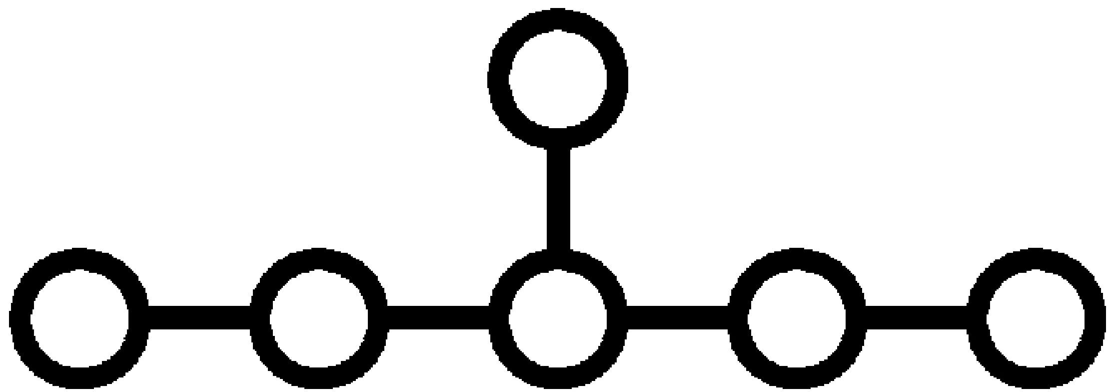
E_7



Next smaller is E_7.

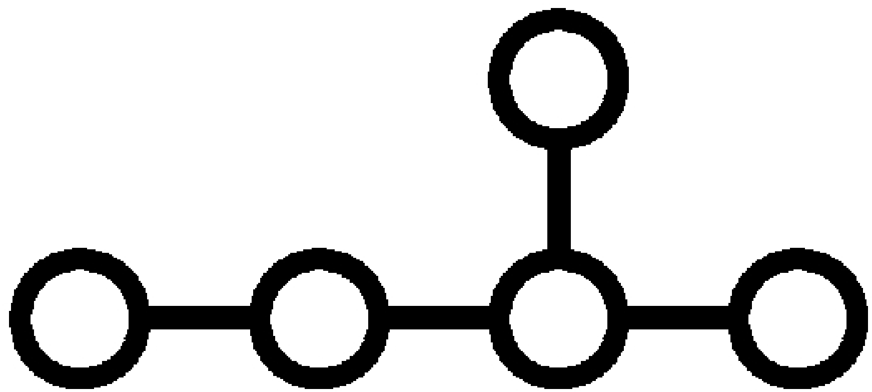
No chiral representations in $d = 4$ either

E_6



E_6 allows for chiral representations even in $d = 4$.

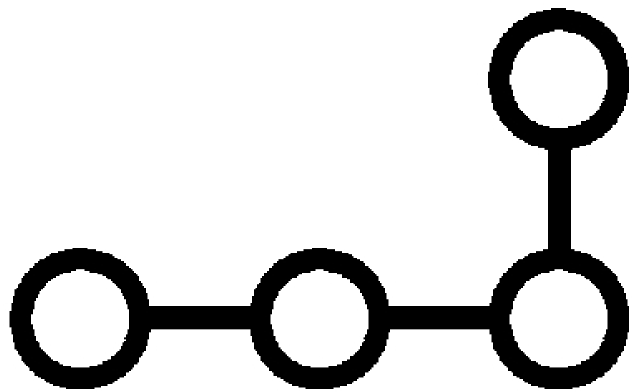
$E_5 = D_5$



E_5 is usually not called exceptional.

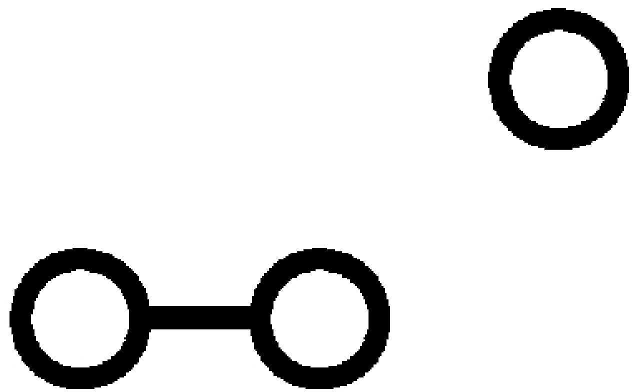
It coincides with $D_5 = SO(10)$.

$E_4 = A_4$



E_4 coincides with $A_4 = SU(5)$

E_3



E_3 coincides with $A_2 \times A_1$ which is $SU(3) \times SU(2)$.

Exceptional groups in string theory

String theory "favours" E_8

- $E_8 \times E_8$ heterotic string
- E_8 enhancement as a nonperturbative effect (M- or F-theory)

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Strings live in higher dimensions:

- chiral spectrum possible even with E_8
- E_8 broken in process of compactification
- provides source for (nonabelian) discrete symmetries
- from $E_8/SO(10)$ and $SO(6)$ of the higher dimensional Lorentz group

Geography

Many properties of the models depend on the geography of extra dimensions, such as

- the location of quarks and leptons,
- the relative location of Higgs bosons,

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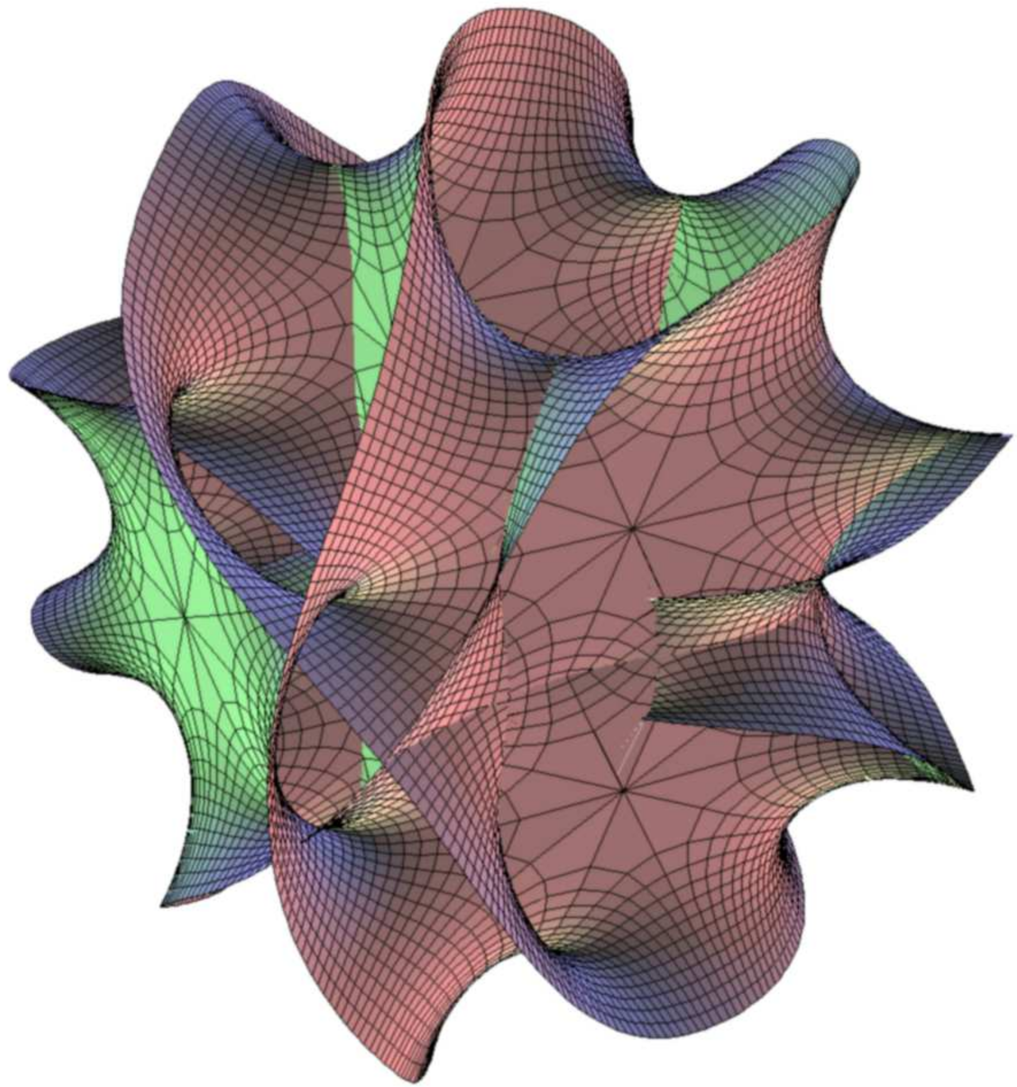
- the location of quarks and leptons,
- the relative location of Higgs bosons,

but there is also a “localization” of gauge fields

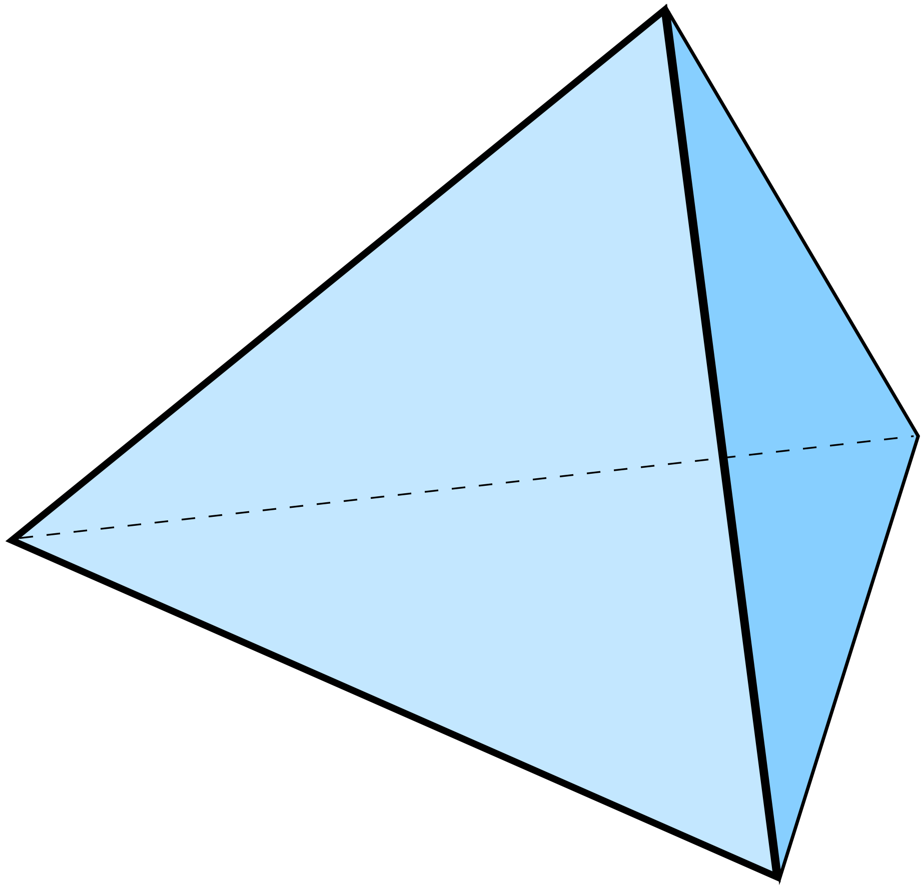
- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

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

Calabi Yau Manifold



Orbifold



(Dixon, Harvey, Vafa, Witten, 1985)

Localization

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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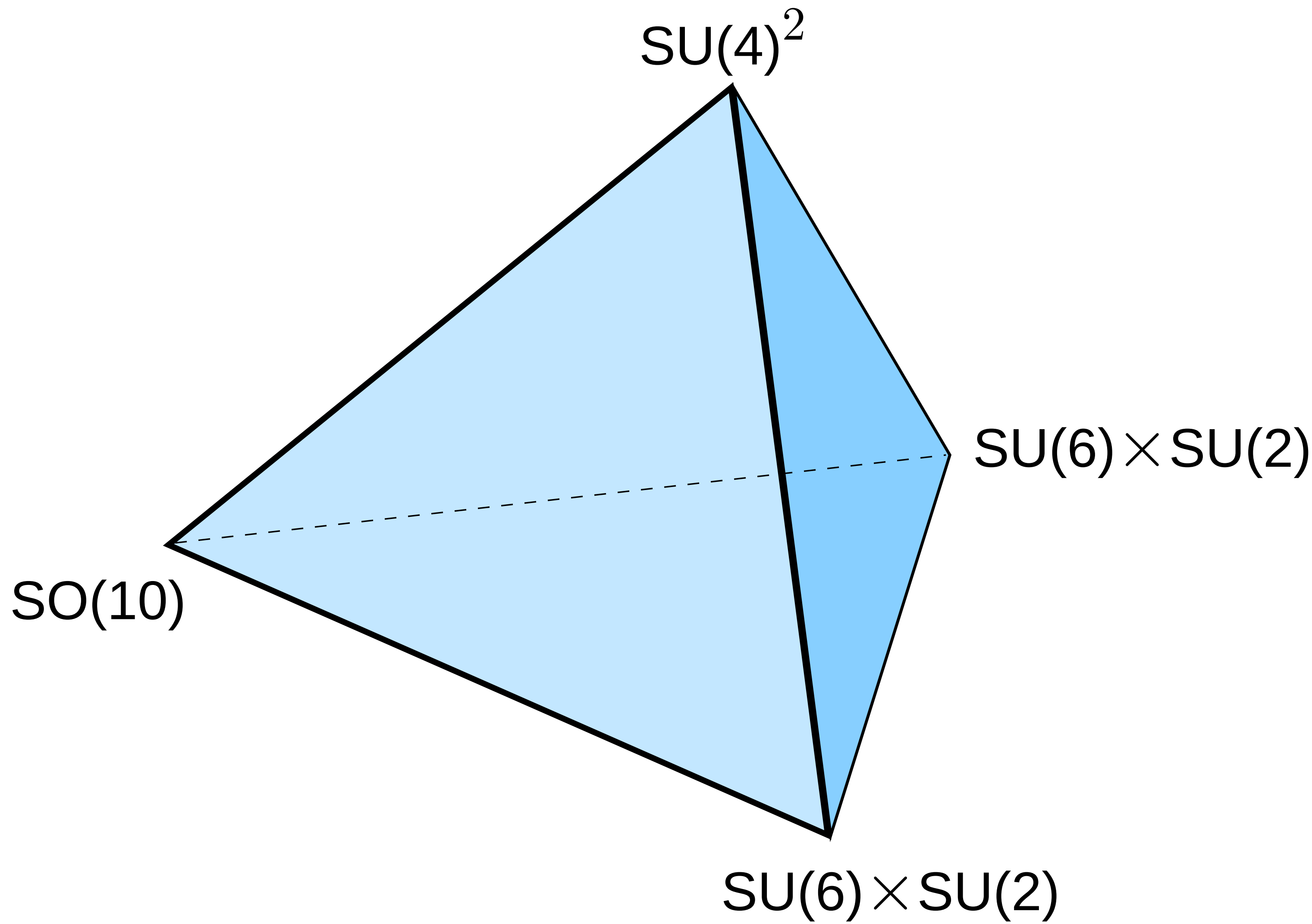
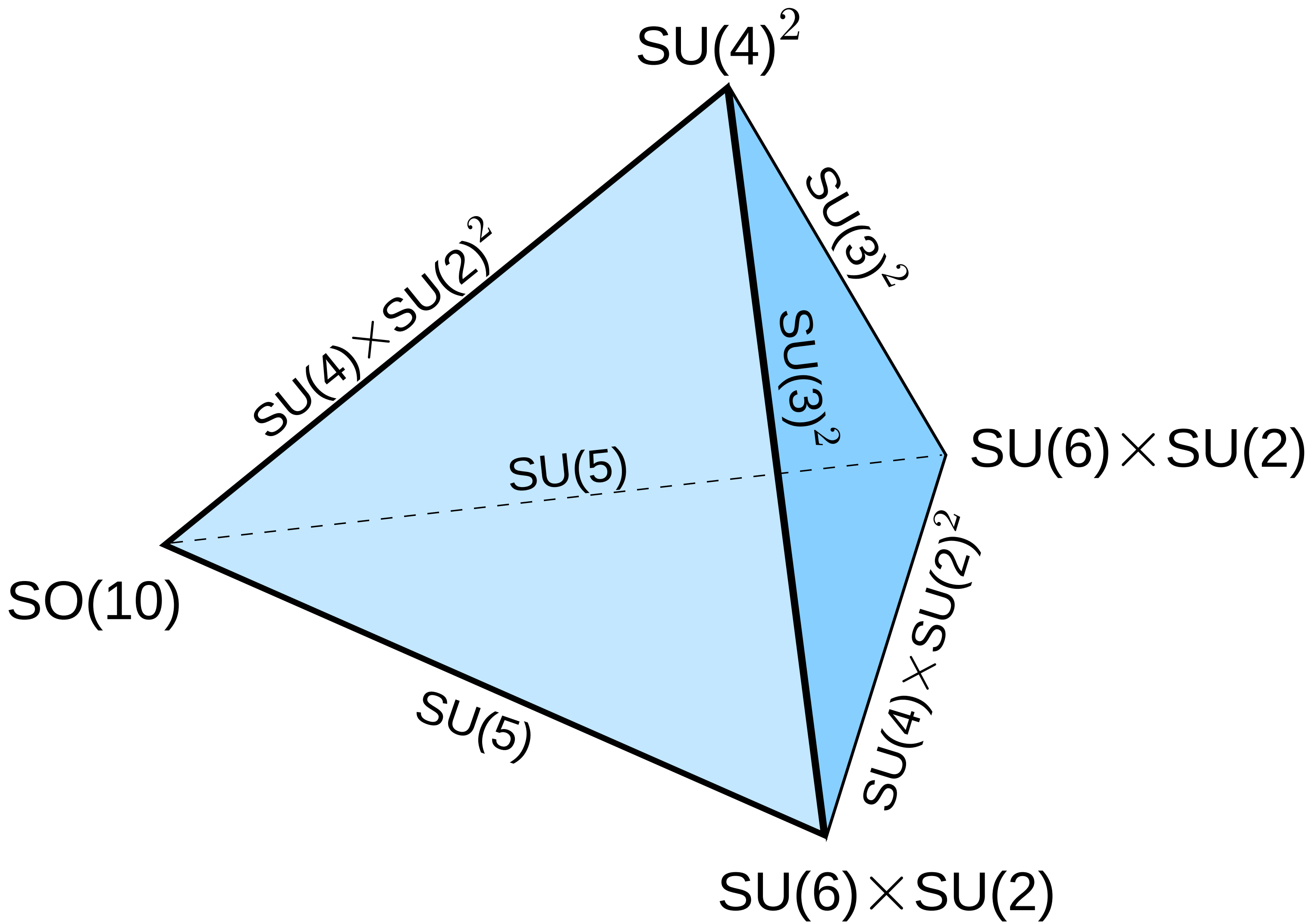
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



The (extended) MiniLandscape

- in $Z_6 II$ orbifold many models with the exact spectrum of the MSSM (absence of chiral exotics)

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006-2009)

- recently extended to the $Z_2 \times Z_4$ orbifold

  (Mayorga Pena, Nilles, Oehlmann, 2012)

- large top quark Yukawa coupling

- family symmetries for the first two families

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

- models with R-parity + solution to the μ-problem

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)

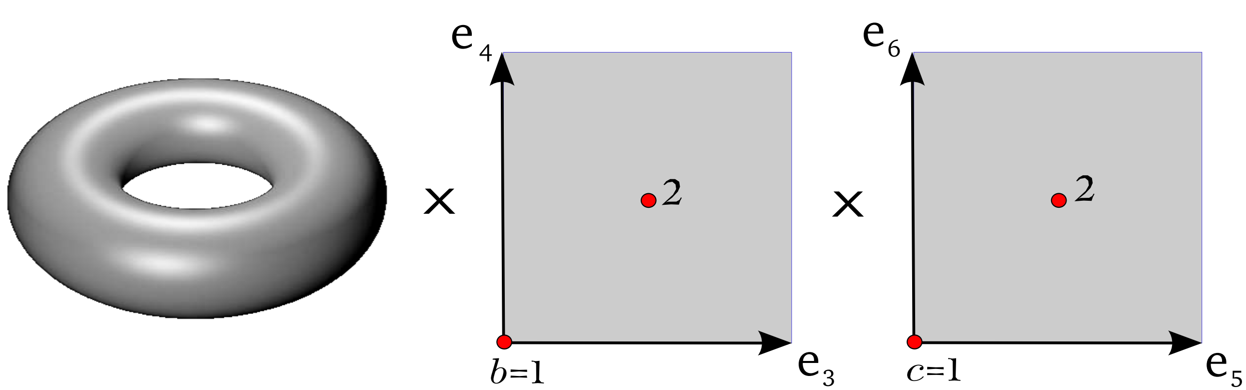
- gaugino condensation and mirage mediation

  (Löwen, HPN, 2008)

Sectors

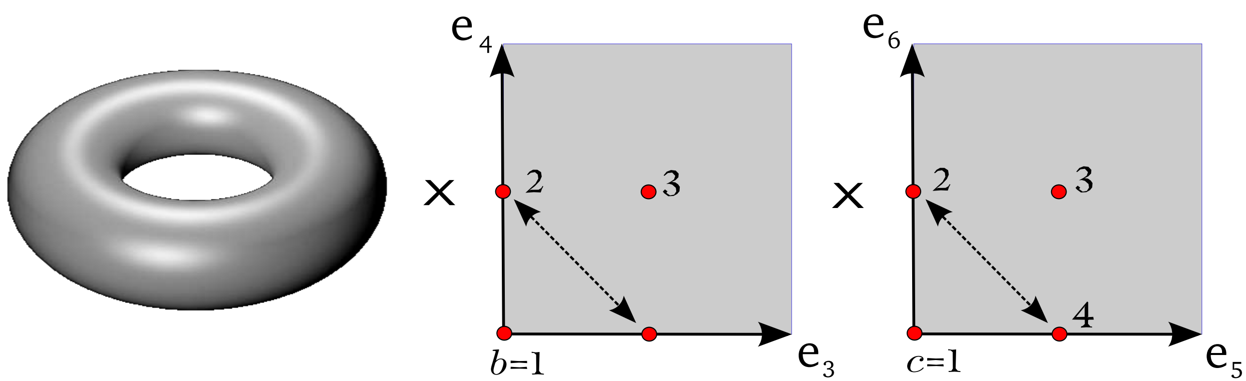
The underlying $Z_2 \times Z_4$ orbifold has the following sectors:

- the untwisted sector (bulk $D = 10$, $N = 4$ Susy)
- twisted sectors corresponding to Z_2 (θ) and Z_4 (ω) twists



The ω sector has 2 x 2 = 4 fixed tori, corresponding to "5-branes" confined to D=6 space-time ($N = 2$ Susy).

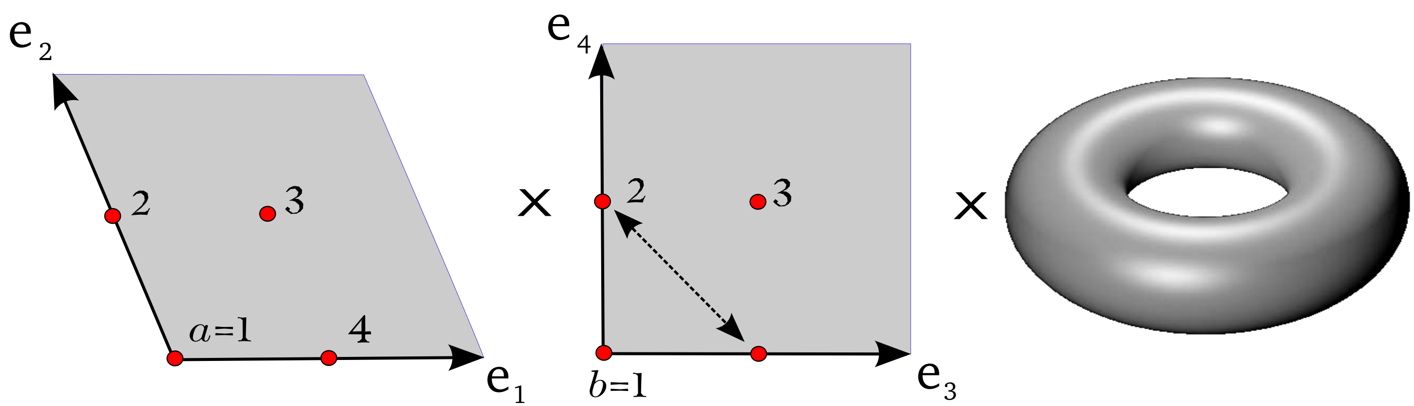
ω^2 twisted sector



The ω^2 sector contains fixed tori corresponding to

- "5-branes" confined to 6 space-time dimensions (remnants of $N = 2$ Susy)

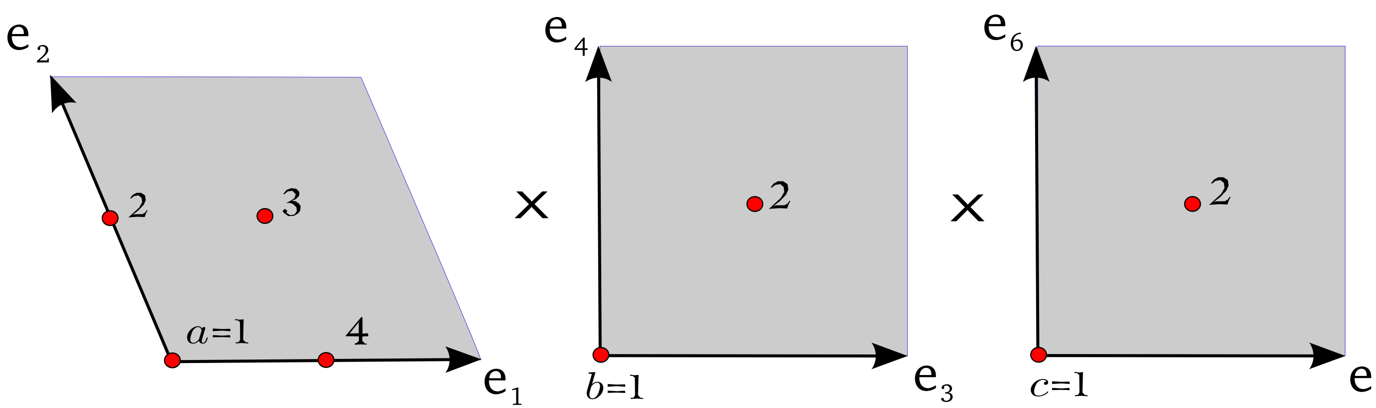
θ twisted sector



The θ sector contains 4 x 3 fixed tori:

- "5-branes" confined to 6 space-time dimensions (sector with $N = 2$ Susy)

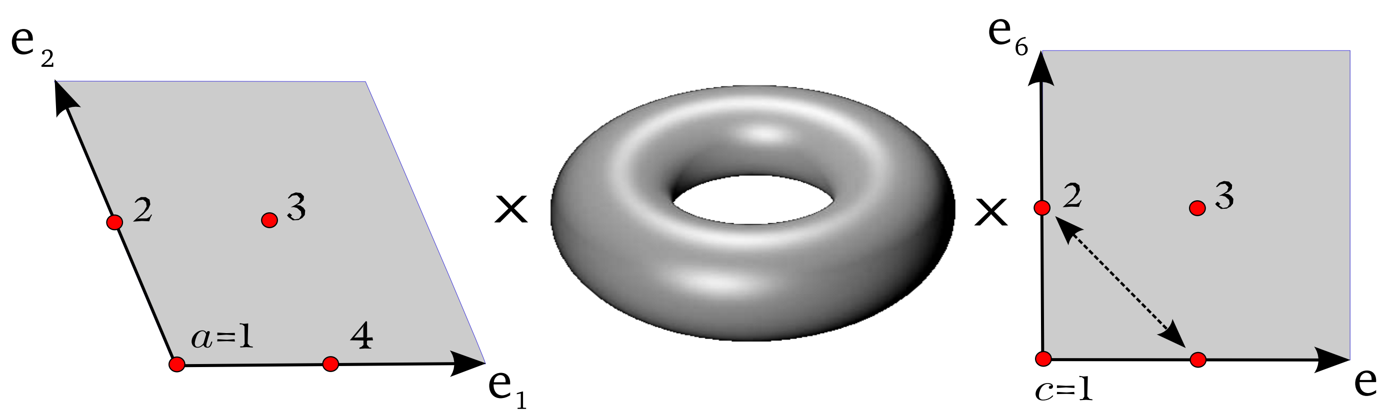
$\theta\omega$ twisted sector



The $\theta\omega$ sector contains 4 x 2 x 2 fixed points:

- "3-branes" confined to 4 space-time dimensions (sector with $N = 1$ Susy)

$\theta\omega^2$ twisted sector



The $\theta\omega^2$ sector contains 4 x 3 fixed tori:

- “5-branes” confined to 6 space-time dimensions (sector with $N = 2$ Susy)

Where do we find quarks, leptons and Higgs bosons in the models of the MiniLandscape?

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 vectorlike 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

The location of Higgs bosons

Typically there could be a multitude of Higgs doublets (and triplets) in the spectrum

- triplets heavy or projected out
- exactly two Higgs doublet multiplets should remain light
- all other heavy

This is the so-called μ problem

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- triplets heavy or projected out
- exactly two Higgs doublet multiplets should remain light
- all other heavy

This is the so-called μ problem

The MiniLandscape identifies exactly one Higgs pair protected by a discrete R-symmetry und provides a unique solution to the μ problem, because the

Higgs bosons live in the untwisted sector (delocalized Higgs as in torus compactification: remnants of $N = 4$ Susy)

Location of top quark

Given the fact that the Higgs multiplets live in the bulk we now explore how to obtain a large top quark Yukawa coupling

- need maximum “overlap” with the Higgs multiplet
- results of the MiniLandscape teach us that this requires the top quark to live in the untwisted sector as well

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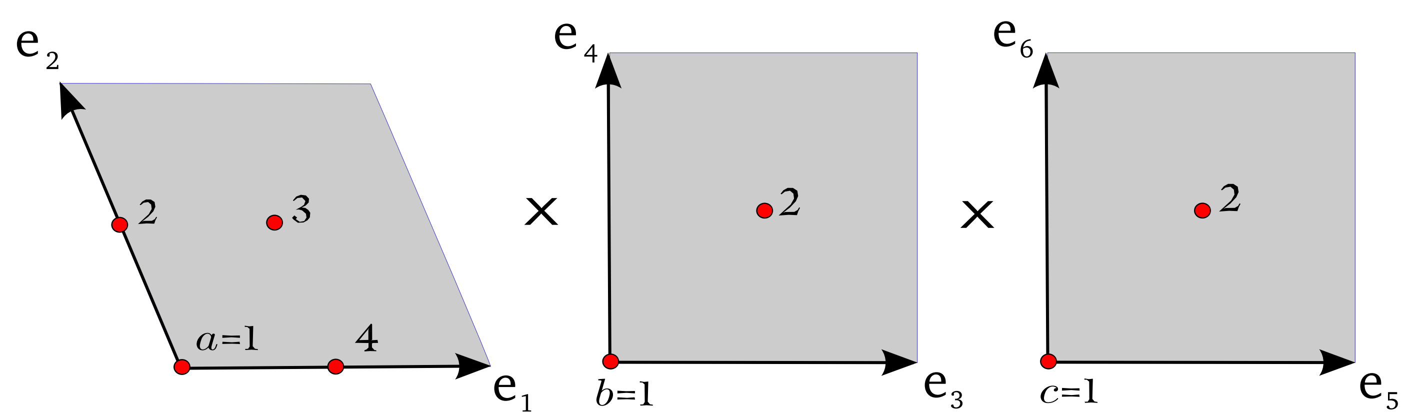
- results of the MiniLandscape teach us that this requires the top quark to live in the untwisted sector as well

Top quark in untwisted sector (bulk). The third family is usually distributed over various sectors (it is not in a complete localized SO(10) representation).

Side remark:
3 "complete" families impossible within $Z_6 II$ orbifold

First and second family

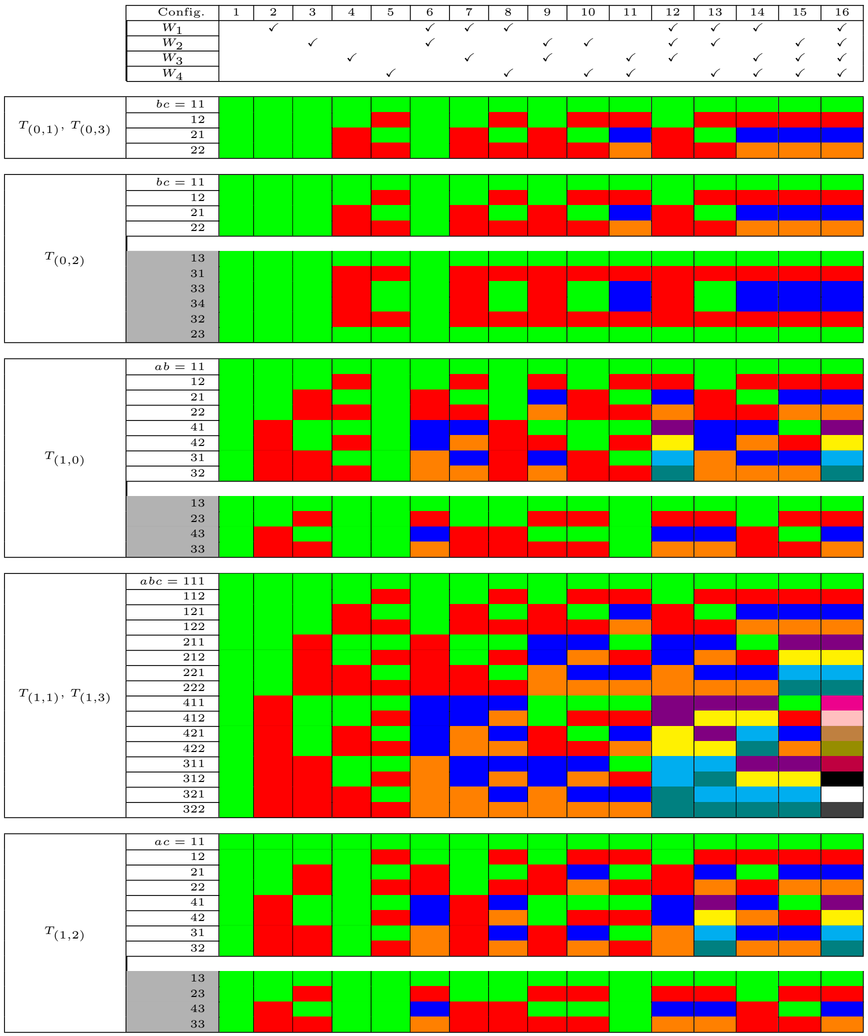
The first and second families are in complete localized 16-dimensional representation of SO(10) (at points of “enhanced” gauge symmetry)

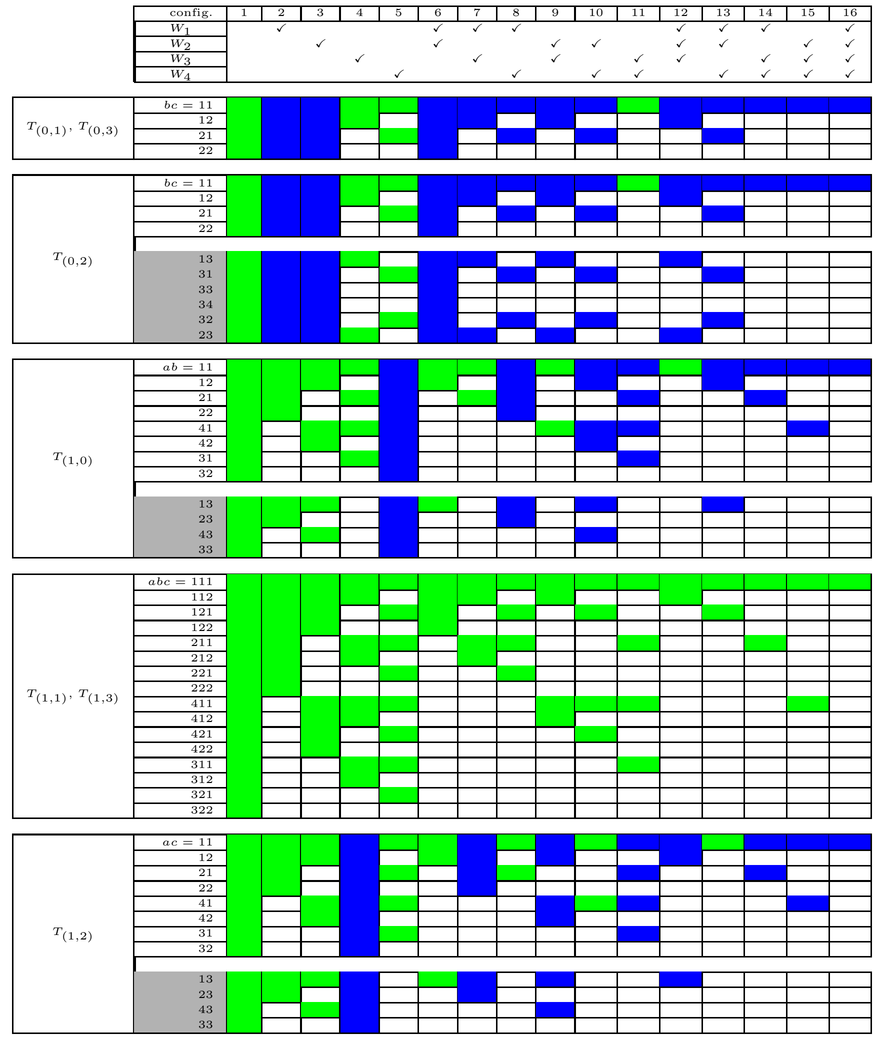


They live in the θ twisted sector and are localized at the fixed points $a = 1$ and 2, $b = 1$, $c = 1$

exhibiting a D_4 family symmetry.

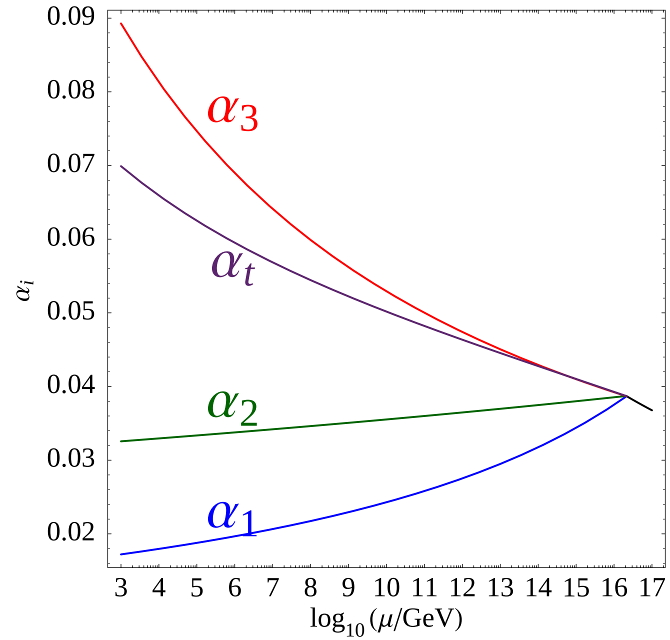
Effects of Wilson lines





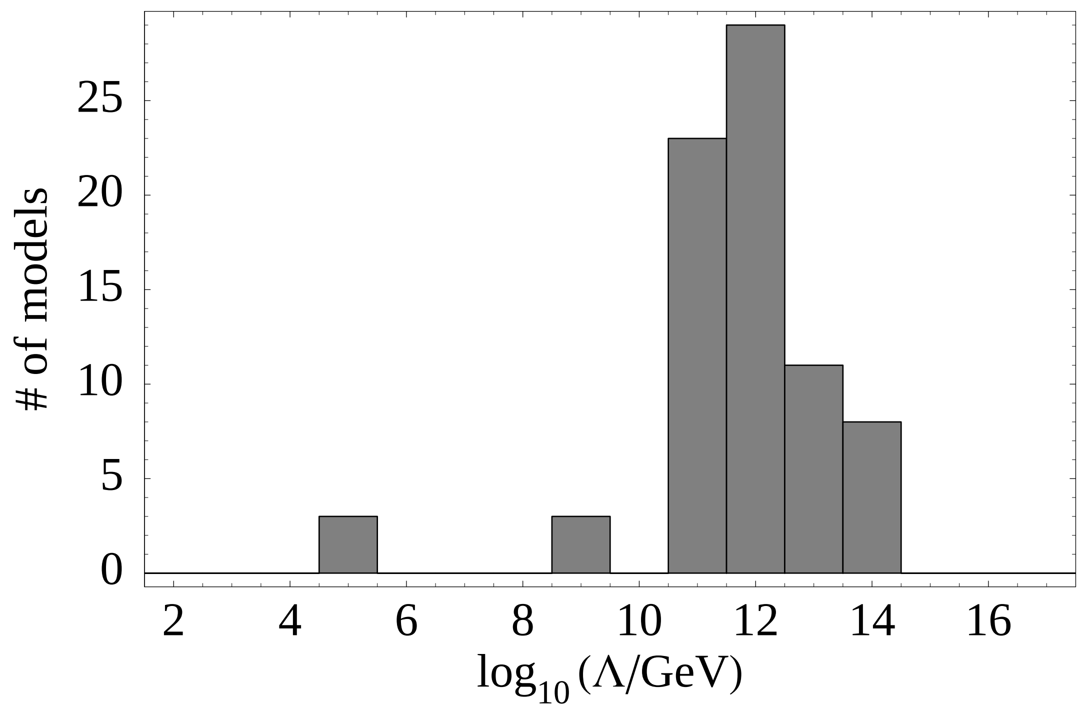
Unification

- Higgs doublets live in the bulk
- heavy top quark lives in the bulk as well.
- $\mu-$term protected by a discrete R-symmetry



- Minkowski vacuum before Susy breakdown (no AdS)
- solution to μ-problem (Casas, Munoz, 1993)
- first two families localized (smaller Yukawa couplings) exhibiting a discrete family symmetry

Heterotic string: gaugino condensation



Gravitino mass $m_{3/2} = \Lambda^3/M^2_{\text{Planck}}$ and $\Lambda \sim \exp(-\tau)$
SU(4) in hidden sector predicts gravitino mass in TeV range

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

Gaugino condensation 1985

CERN-TH.4123/85

ON THE LOW ENERGY d = 4, N = 1 SUPERGRAVITY THEORY

EXTRACTED FROM THE d = 10, N = 1 SUPERSTRING*)

J.P. Derendinger, L.E. Ibañez+)

CERN - Geneva

and

H.P. Nilles

Department of Theoretical Physics
University of Geneva

Gaugino condensation 1985

APPENDIX B

KAHLER POTENTIAL AND DERIVATIVES IN THE TRUNCATED LAGRANGIAN

The Kähler potential upon truncation has the form

$$G \equiv K + \log |W|^2 = -\log(S+S^*) - 3\log(T+T^* - 2|C|^2) + \log |W|^2 \qquad \text{(B.1)}$$

From now on we shall define

$$s \equiv \mathrm{Re}\, S \ , \quad t \equiv \mathrm{Re}\, T \ , \quad t_c \equiv t - |C|^2 \qquad \text{(B.2)}$$

so that one has

$$K = -\log(2s) - 3\log(2t_c) \qquad \text{(B.3)}$$

Gaugino condensation 1985

so that one has

$$K = -\log(2s) - 3\log(2t_c) \tag{B.3}$$

Notice that the following useful identities hold

$$t_c = e^{\sigma}\varphi^{3/4} = g_4^2 e^{4\sigma} \tag{B.4}$$

$$s = e^{3\sigma}\varphi^{-3/4} = g_4^{-2} \tag{B.5}$$

$$\varphi = t_c\, s^{-1/3} \tag{B.6}$$

$$e^{4\sigma} = s\, t_c \tag{B.7}$$

$$e^{K} = \frac{1}{16} e^{-6\sigma}\varphi^{-3/2} = \frac{1}{16} s^{-1} t_c^{-3} \tag{B.8}$$

The derivatives of the Kähler potential with respect to the scalar fields T, S, and C are useful in order to obtain the explicit form of the N = 1 supergravity Lagrangian. For the convenience of the reader we present many of these derivatives in this appendix. Denoting, for example,

The overall pattern

The MiniLandscape provides a specific pattern for the soft masses with a large gravitino mass in the multi-TeV range

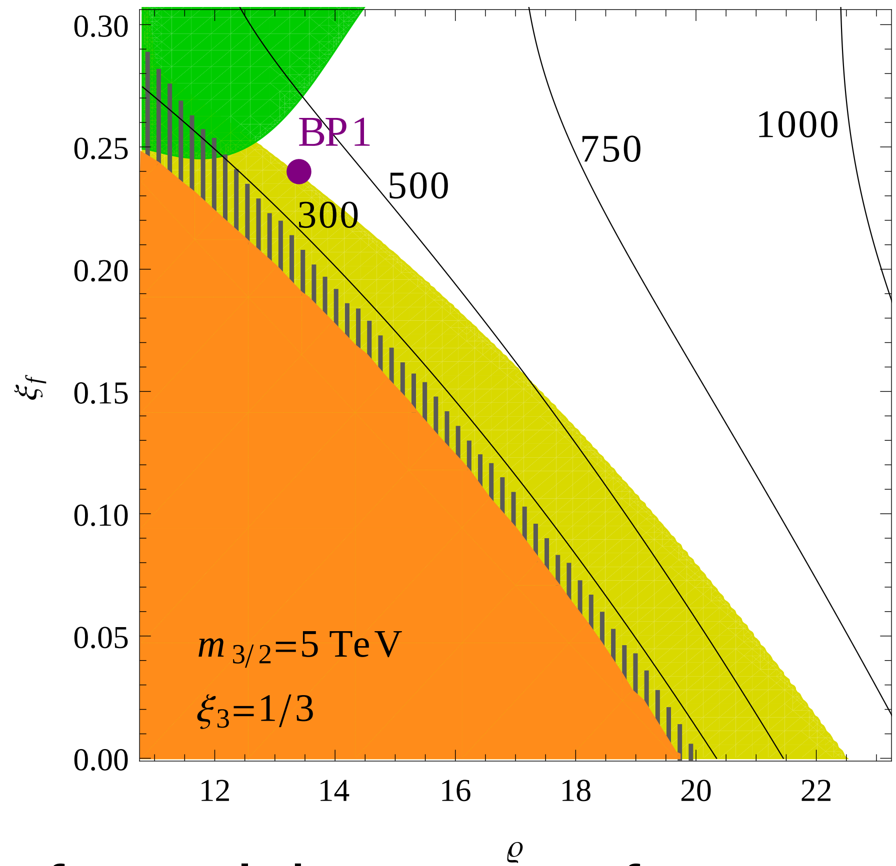
- normal squarks and sleptons in Multi-TeV range
- top squarks $(\tilde{t}_L, \tilde{b}_L)$ and $\tilde{t}_R$ in TeV-range (suppressed by $\log(M_{\text{Planck}}/m_{3/2}) \sim 4\pi^2$)
- A-parameters in TeV range
- gaugino masses in TeV range
- mirage pattern for gaugino masses (compressed spectrum)
- heavy moduli (enhanced by $\log(M_{\text{Planck}}/m_{3/2})$ compared to the gravitino mass)

A Closer Look

A more detailed picture requires the analysis of specific models. Issues that have to be clarified:

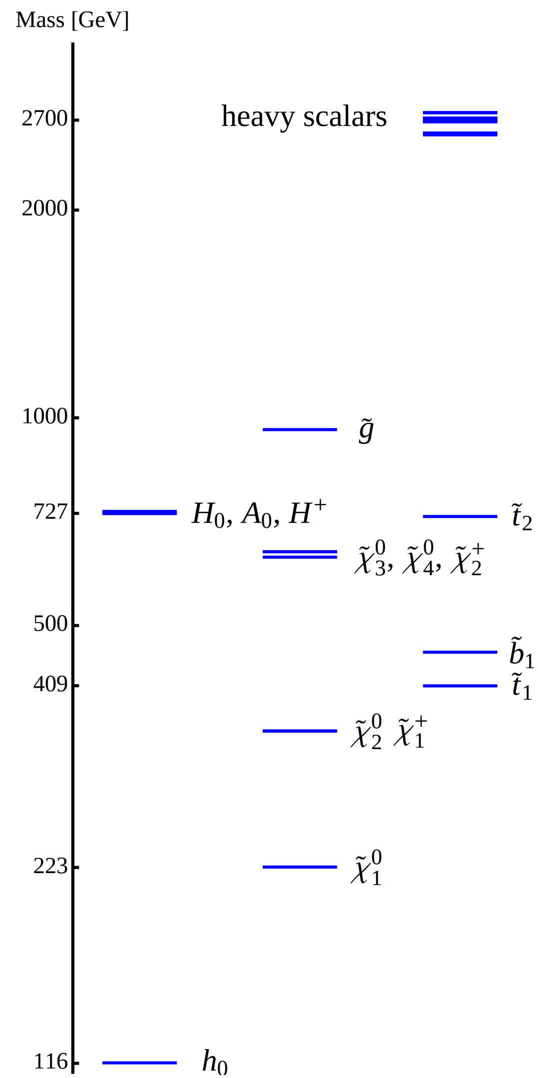
- the appearance of tachyons,
  - partially inherited from anomaly mediation
  - two loop effects in the presence of heavy scalars
- the hierarchy between gauginos and sfermions.
- Can we satisfy all phenomenological constraints?
  - mass of Higgs, correct electroweak symmetry breakdown etc.
  - nature and abundance of WIMP-LSP.
- What is the LHC reach to test this scheme?

Benchmark model with a TeV gluino



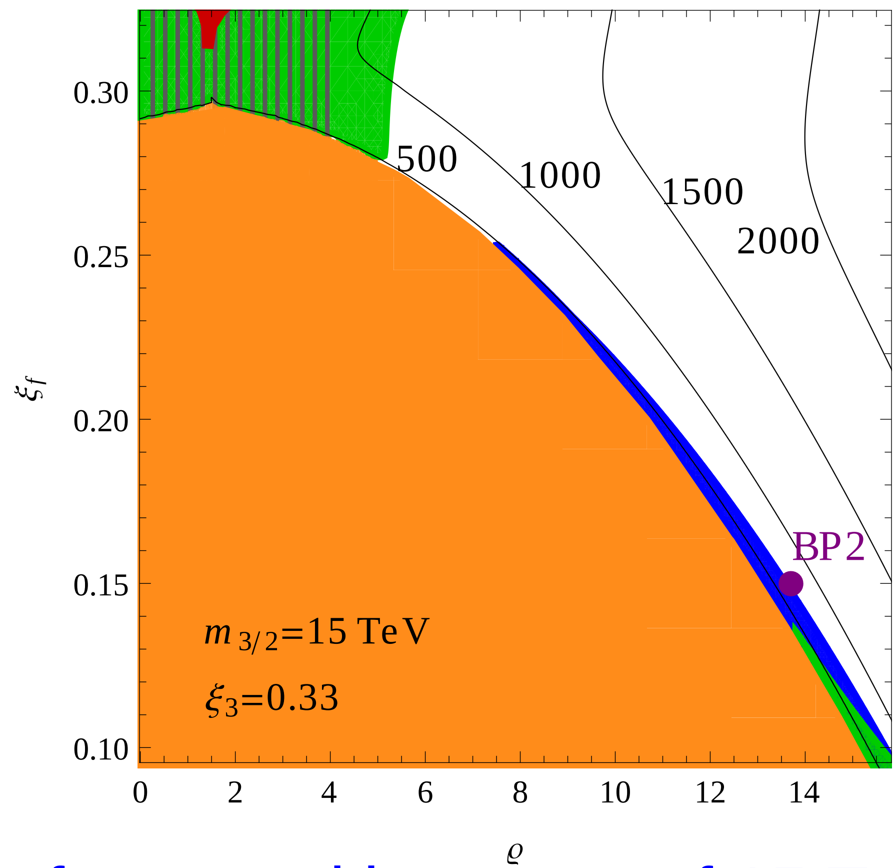
Parameter scan for a gluino mass of 1 TeV. The coloured regions are excluded while the hatched region indicates the current reach of the LHC. The contours indicate the mass of the lightest stop.

Spectrum



Mass [GeV]
2700
2000
1000
727
500
409
223
116
heavy scalars
$\tilde{g}$
H_0, A_0, H^+
$\tilde{t}_2$
$\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^+$
$\tilde{b}_1$
$\tilde{t}_1$
$\tilde{\chi}_2^0\ \tilde{\chi}_1^+$
$\tilde{\chi}_1^0$
h_0

Model with a 3 TeV Gluino

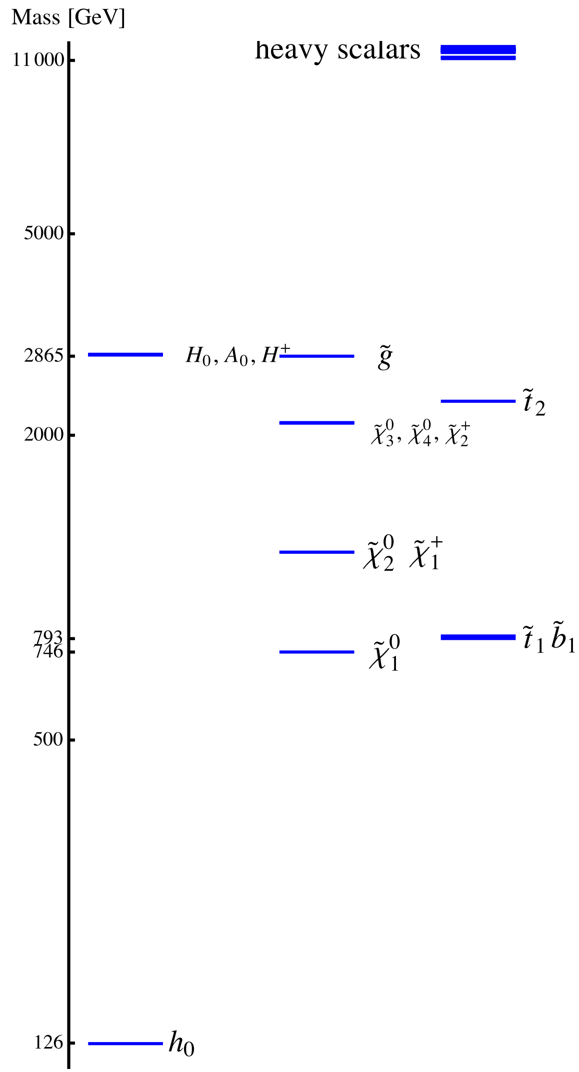


Parameter scan for a gravitino mass of 15 TeV.

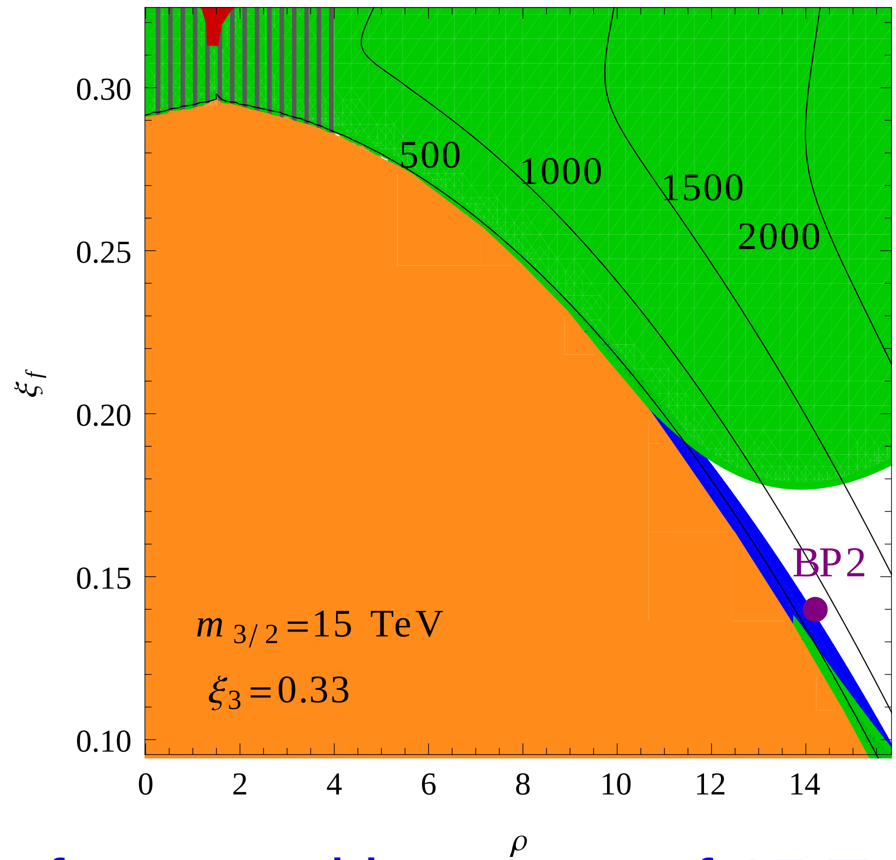
The coloured regions are excluded while the hatched region indicates the current reach of the LHC.

The contours indicate the mass of the lightest stop.

Spectrum


Mass [GeV]
heavy scalars
11 000
5000
2865
$H_0, A_0, H^\pm$
$\tilde{g}$
$\tilde{t}_2$
2000
$\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^+$
$\tilde{\chi}_2^0\ \tilde{\chi}_1^+$
793
746
$\tilde{\chi}_1^0$
$\tilde{t}_1\,\tilde{b}_1$
500
126
h_0

After Higgs discovery



Parameter scan for a gravitino mass of 15 TeV.

The coloured regions are excluded while the hatched region indicates the current reach of the LHC.

The contours indicate the mass of the lightest stop.

Messages

- large gravitino mass (multi TeV-range)
- gaugino masses and stops suppressed by $\log(M_{\text{Planck}}/m_{3/2})$
- other sfermion masses are of order $m_{3/2}$
- the heterotic string yields “Natural SUSY” as a remnant of the underlying $N = 4$ Susy
  - mirage pattern for gauginos,
  - light stop masses
- and this is a severe challenge for LHC searches.

The overall scale

There is no (reliable) prediction for the gravitino mass

- except for fine-tuning arguments
- “no lose” criterion (SSC with 20+20 TeV)
- does LHC satisfy this criterion?

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Betting in the early 80’s

- I bet that supersymmetry will be discovered before SSC gets into operation
- I bet that supersymmetry will have been forgotten before SSC gets into operation

Conclusions

Localization of quarks, leptons and Higgs bosons

- realistic models require Higgs multiplets and top multiplets in bulk (connected to μ problem)
- this implies Gauge-Yukawa unification
- other fields tend to be localized at fixed points (tori) and exhibit discrete family symmetries

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The legacy from extra dimensions ($D = 10$)

- discrete family symmetries
- mirage mediation (a hierarchy from $\log(M_{\mathrm{Planck}}/m_{3/2})$)
- mass spectrum of “Natural Susy” from $N = 4$

Where does LHC lead us?

Does he know?

It seems as if.....?

Mirage pictures