Stringy Origin of Discrete R-Symmetries

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Hierarchical Structures

The importance of discrete symmetries

- protection of parameters in a natural way
- slight breakdown can lead to hierarchies and small parameters
- hierarchy of Yukawa couplings, μ parameter, Susy breakdown, proton stability

Various breakdown mechanisms

- nonperturbative effects: $\exp(-X)$
  (gaugino condensation, world sheet instantons)
- Froggatt-Nielsen mechanism: ($1/n^k$)

Strings and Particle Physics

String theory provides us with

- gravity
- gauge symmetries
- matter multiplets for quarks and leptons
- SUSY and extra dimensions
- discrete (gauge) symmetries.

The MSSM is not a generic prediction of string theory:

- need exploration of the "Landscape" at non-generic points with higher symmetries
- that provide enhanced discrete symmetries.

Importance of discrete symmetries

Discrete symmetries can provide us with

- hierarchy of scales (Susy breakdown and μ parameter)
- flavour symmetries
- accidental Peccei-Quinn symmetries
  (strong CP-problem)
- proton stability (structure of B- and L-violation)

Breakdown of these symmetries can provide

- small parameters for hierarchical pattern
- Froggatt-Nielsen mechanism and flavour structure

Where do such (non-generic) symmetries come from?

Geometry of extra dimensions

Enhanced symmetries can appear as a result of

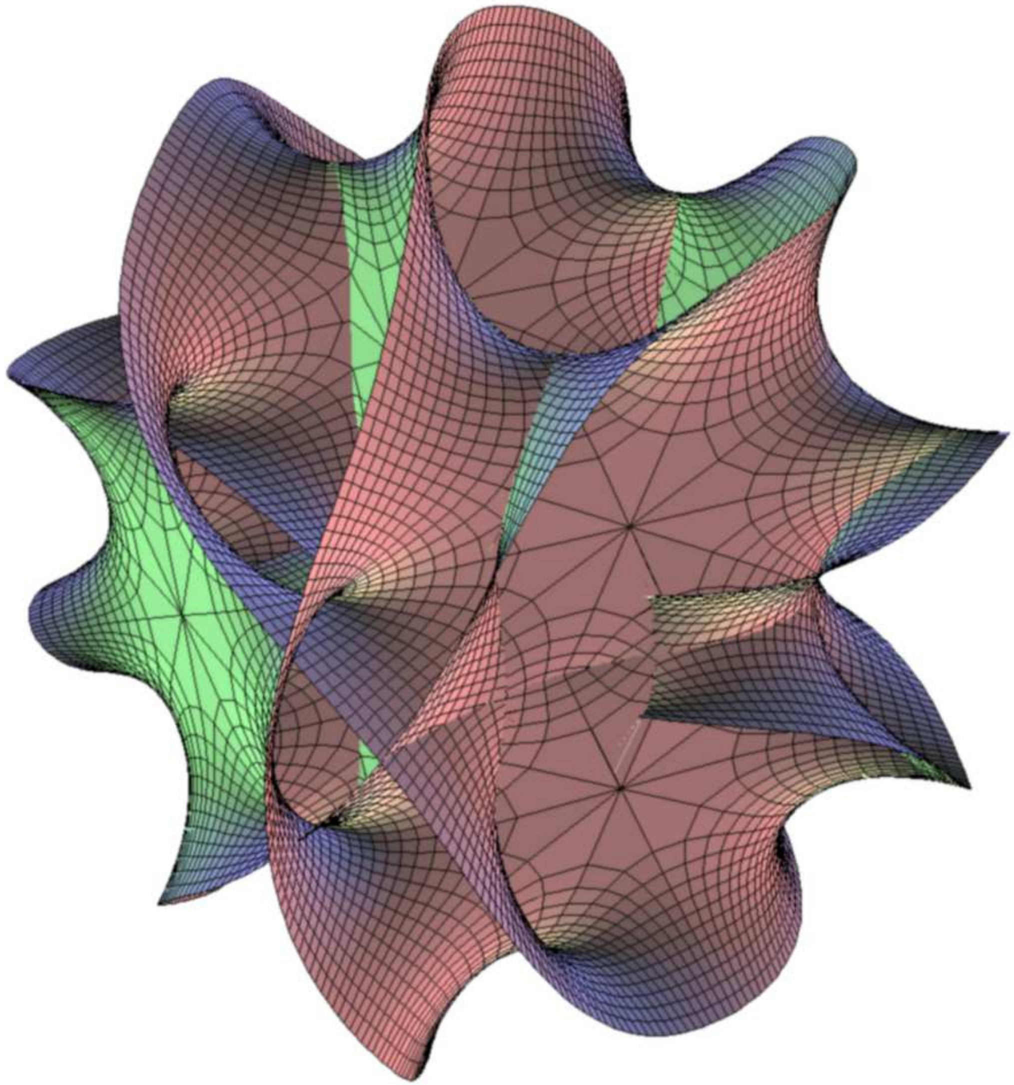
- symmetries of compact manifold (geometry)
- localisation of fields in extra dimensions (geography)

Where do fields reside?

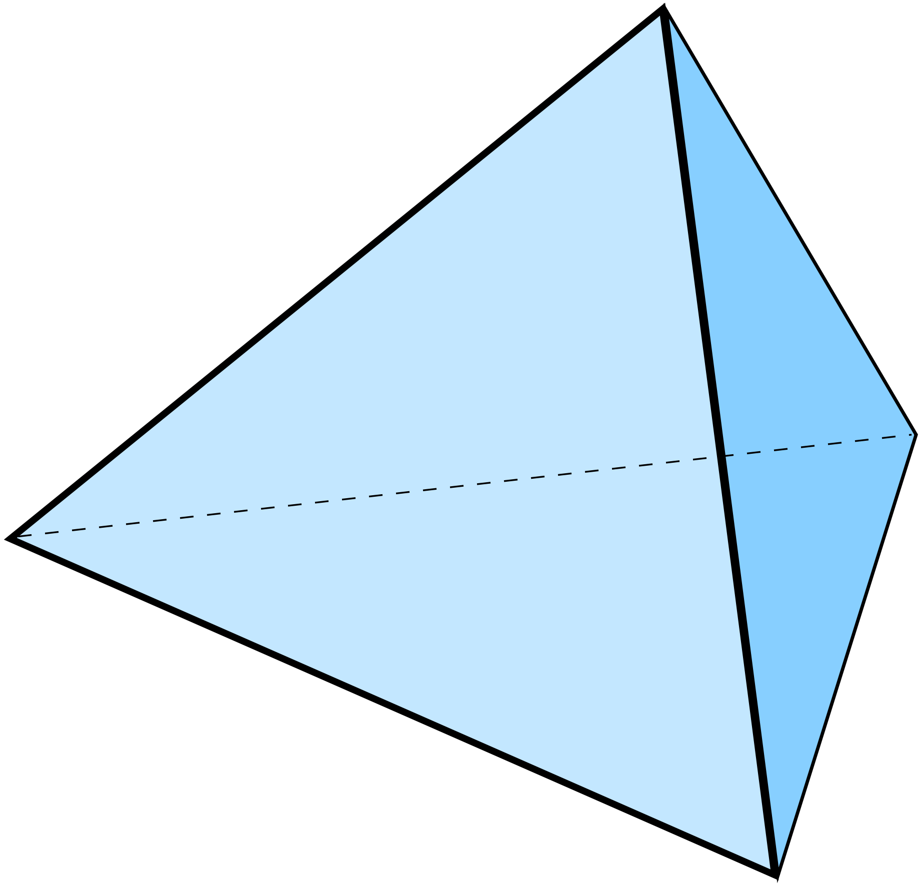
- gravity in bulk
- matter fields (bulk, brane or intersection of branes)
- Higgs bosons and gauge bosons with various options (possibility of "gauge-Higgs unification")

Relative location of matter and Higgs (gauge) fields determine many properties of low energy physics

Calabi Yau Manifold



Orbifold

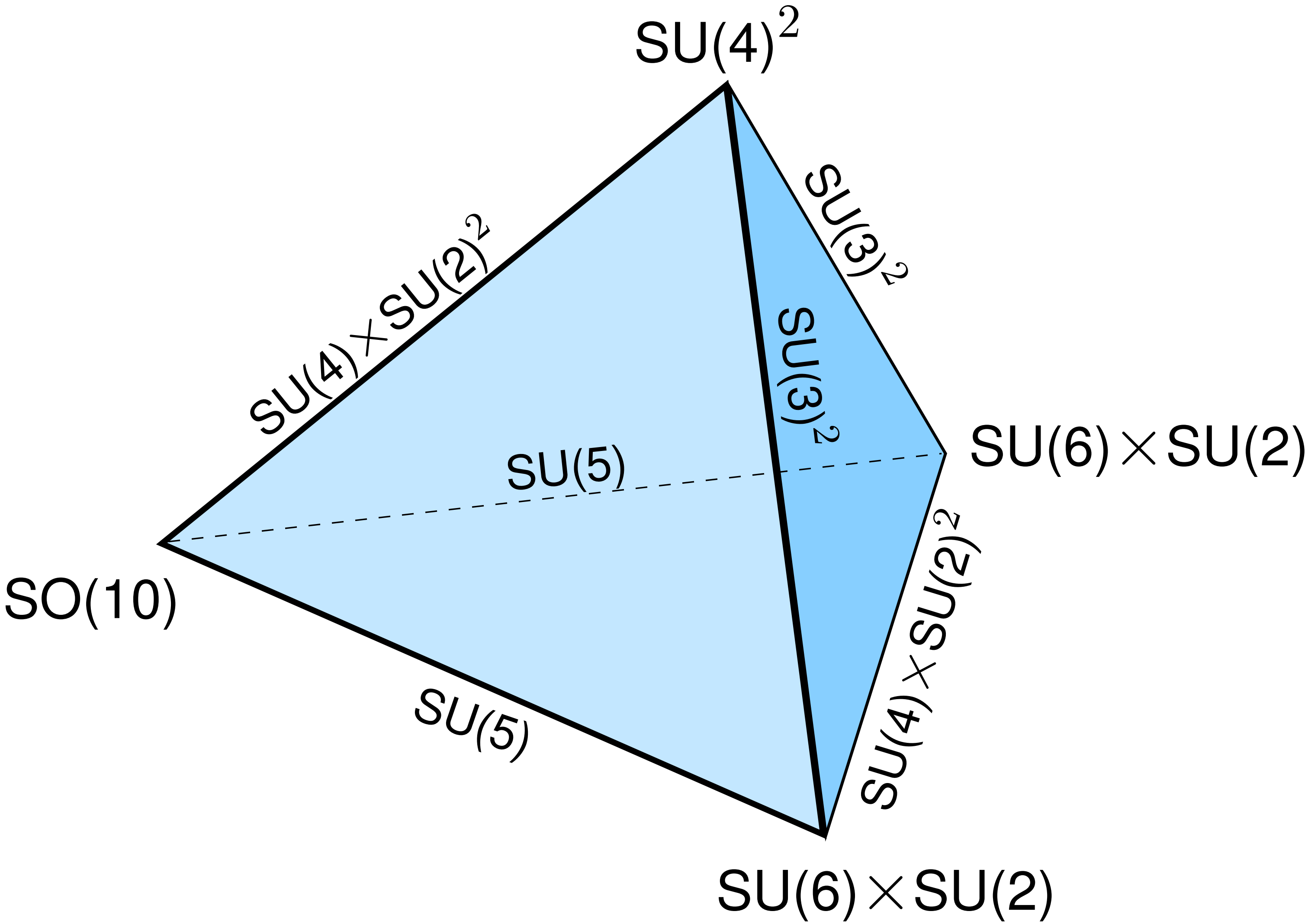


The Options

Gravity is usually acting in the bulk. Other properties depend on specific theory.

- M-theory (type IIA)
  - gauge fields on 6-branes, matter on 3-branes (at intersection of 6-branes)
- F-theory (type IIB)
  - gauge fields on 7-branes, matter on 5-branes (Yukawas at intersection of 5-branes)
- heterotic string
  - gauge fields in bulk (with local breakdown), matter on fixed tori (5-branes) or fixed points (3-branes)

Local Grand Unification



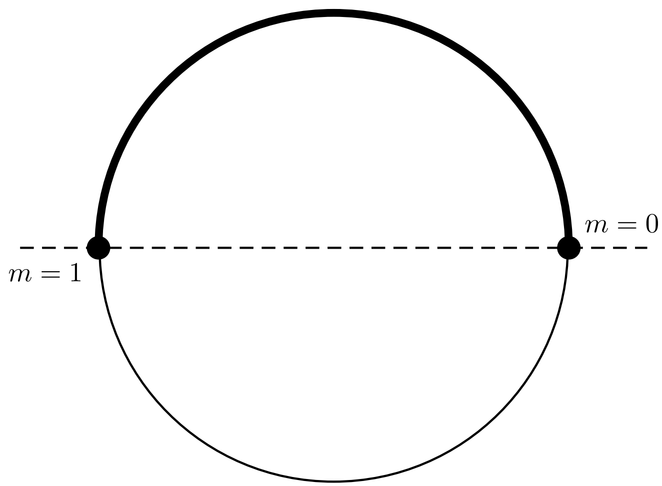
Geographical considerations

Chiral fields prefer "stronger" localisation

- quarks and leptons at lower dimensional branes or intersections
- Higgs fields come in vector like pairs
  - not protected by chiral symmetries
  - one pair needs special protection (μ-problem)
  - gauge-Higgs unification (similarity of gauge and Higgs bosons from geographical point of view)
- gauge bosons in bulk or higher dimensional branes (local GUTs give specific profile in extra dimensions in connection with breakdown of gauge group (and Susy))

Origin of discrete symmetries

Discrete symmetries control the properties of the theory: Yukawa couplings, Higgs potential etc.



A simple example: a circle divided by a reflection Z_2.

Leads to an interval with two fixed points at the boundaries.

Can describe models with a
5-dimensional bulk and 3-branes at the boundary.

Origin of symmetries

There are bulk and (localised) brane fields (=twisted fields) with specific selection rules

- interchange of fixed points S_2 symmetry (geometry)
- selection rules for twisted states ($Z_2 \times Z_2$ symmetry)

Twisted fields form a doublet transforming nontrivially

- under the abelian $Z_2 \times Z_2$ (boundary fields)
- and S_2 exchanging the fixed points

The multiplicative closure of these transformations leads to a non-abelian group with 8 elements D_4 (the symmetry of the square).

Some remarks

Discrete symmetries arise from the interplay of geometrical symmetries and selection rules

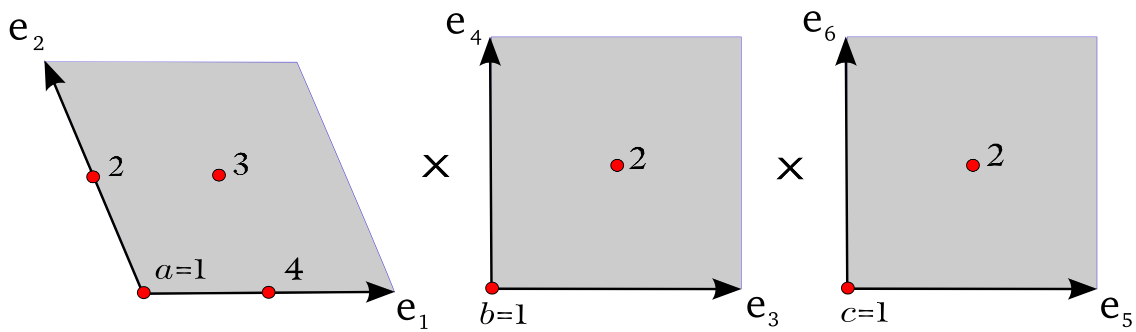
- already simple set-ups lead to large groups
- non-abelian discrete groups even from "abelian" geometry

These groups have immediate application as flavour symmetries

- D_4 is nonabelian subgroup of flavour-$SU(2)$ (of the first two generations of quarks)
- abundance of discrete groups makes contact to "bottom-up" approaches for flavour physics

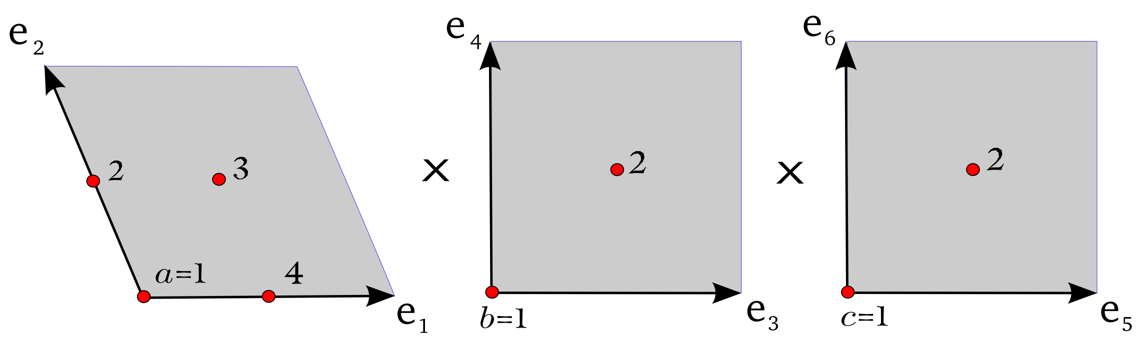
Example from MiniLandscape

The first two families live at fixed points:



Example from MiniLandscape

The first two families live at fixed points:



- they exhibit a D_4 family symmetry
- as a subgroup of $SU(2)$ flavour symmetry
- its origin is the interplay of geometry and selection rules

(Kobayashi, Nilles, Ploger, Raby, Ratz, 2007)

Location of Higgs fields

Successful models of the “MiniLandscape” have

- one pair of Higgs doublets (with vanishing μ-term)
- additional potential Higgs pairs are removed together with other vector-like exotics

A closer inspection of the models shows that

- μ is protected by a discrete $R-$symmetry.
- the supersymmetric model has vanishing vacuum energy (4d Minkowski space).

(Kappl, Nilles, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange: 2009)

Where do discrete $R-$symmetries come from?

$R-$symmetries

$R-$symmetries transform the super-space coordinate θ

- they do not commute with Susy
- components of super-multiplets have different $R-$charges
- the super-potential transforms non-trivially

$R-$symmetry can be understood as an extension of Susy

- MSSM ($N = 1$ Susy) extended with $U(1)_R$ forbids gaugino masses, μ-term and trilinear soft terms (A)
- broken to a discrete symmetry (like Z_2 matter parity) it can guarantee proton stability and a stable LSP for dark matter

Geography of Higgs-multiplets

String models typically contain many pairs of Higgs doublets (the multi-μ-problem)

- many pairs can be removed (as well as other vector-like exotics) by breaking additional $U(1)$-symmetries
- one pair might still have a vanishing μ-parameter (protected by an $R-$symmetry)
- the latter is not removed with other vector-like exotics

A key observation (in models of Mini-Landscape)

- the protected Higgs pairs are bulk-fields
- $R-$symmetries are connected to Lorentz group in extra dimensions: $SO(9,1) \to SO(3,1) \times SO(6)$

Superpotential and μ-term

Higgs pairs $H_u H_d$ are neutral under all selection rules

$$W = P_W(\phi_i) + P_\mu(\phi_i) H_u H_d$$

If $P_W(\phi_i)$ forbidden by a symmetry then $P_\mu(\phi_i) H_u H_d$ is forbidden as well. This connects

- the vev of the super-potential (gravitino mass)
- with the value of the μ-term

Unbroken symmetry corresponds to vanishing gravitino mass and $\mu = 0$.

The supersymmetric ground state is flat Minkowski space.

Connection to extended Susy

The amount of unbroken Susy depends on the manifold of compactification

- 6-Torus form d=10 leads to $N = 4$ extended Susy: R-symmetry is $SU(4)_R \sim SO(6)$ (maximal group of completely geometric origin)
- fixed tori (5-branes) with d=6 lead to $N = 2$ extended Susy (with R-symmetry $SU(2)_R$)
- fixed points (3-branes) with d=4 feel $N = 1$ Susy (no R-symmetry from geometry)

Bulk fields could be subject to extended Susy (of geometric origin). Various sectors of a given model can feel different amounts of supersymmetry (compare to local GUTs).

Geometry and selection rules

As before the discrete $R-$symmetries have their origin in

- geometry (here the Lorentz group in extra dimensions)
- string theory selection rules

This opens the possibility for large discrete groups (from geometry and outer automorphisms).

Selection rules are still under debate

- clarified for normal orbifolds with Wilson lines

(Cabo Bizet, Kobayashi, Mayorga Pena, Parameswaran, Schmitz, Zavala, 2013)

(Nilles, Ramos-Sanchez, Ratz, Vaudrevange, 2013)

- not yet understood for models with freely acting twist

Potential (universal) anomalies cancelled by dilatonic shift.

$R-$symmetries and Susy breakdown

Connection of Susy- and R-symmetry breakdown

- gravitino mass is a signal of Susy breakdown
- superpotential transforms nontrivially under R-symmetry

This connects $\mu-$term with Susy breakdown and provides a solution to the $\mu-$problem. (Casas, Munoz, 1993)

Breakdown via non-perturbative effects:
like gaugino condensation or world sheet instantons

- suppression by $\exp(-X)$
- R-symmetry broken to non-R subgroup

Size of gravitino mass plays crucial role.

Combining discrete symmetries

Both discrete R- and non-R-symmetries play crucial roles. Building blocks could be small groups like e.g.

- D_4 as subgroup of flavour-$SU(2)$
  (Kobayashi, Nilles, Ploger, Raby, Ratz, 2006)
- Z_2 matter parity, baryon triality B_3, proton hexality H_6
  (Ibanez, Ross, 1991; Dreiner, Luhn, Thormeier, 2006)
- Z_4^R for the suppression of μ
  (Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange, 2014)

Issues beyond μ and proton stability are concerned with

- dimension 5-Operators for neutrino masses
- Minkowski vacua (avoid susy solutions in "deep" AdS)

Properties of $R-$symmetry

Connection between $R-$symmetry and holonomy group of compact manifold:

- $SU(3)$ holonomy $(\Gamma^{ijk} H_{ijk})$,
- its relation to the superpotential (Chern-Simons terms)
- and gaugino condensates of hidden gauge group.
- Maximal geometric group is $SU(4)_R$ descending from $d = 10$ and thus completely of geometric origin.
- From $d = 6$ we can have $U(2)_R \times U(2)_R$ partially from geometry and partially from selection rules,
- similar to the situation of normal discrete symmetries (e.g. D_4 flavour symmetry discussed earlier).

The power of $R-$symmetries

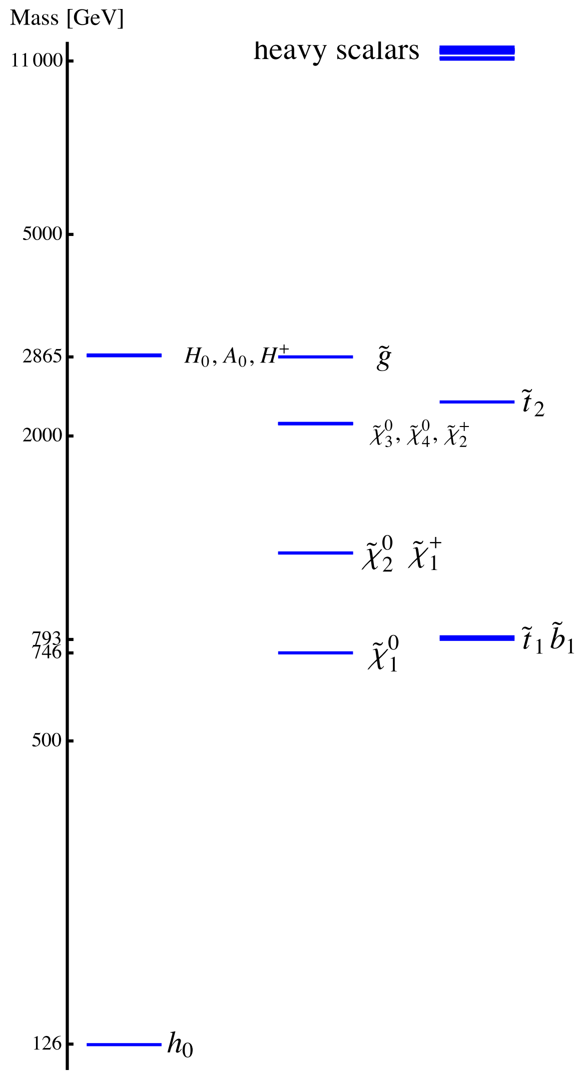
More $R-$symmetries imply better protection than just Susy alone. Different sectors of a model might feel different amounts of supersymmetry ("fractionally extended Susy")

- bulk fields with full $N = 4$ supersymmetry lead to a "no-scale" pattern of Susy breakdown.
- other sectors might be subject to $N = 2$ Susy (threshold corrections)
- localised fields (3-branes) with $N = 1$

Pattern of soft Susy breaking terms in various sectors of extended Susy leads to reduced fine tuning (natural Susy in the framework of local grand unification).

(Krippendorf, Nilles, Ratz, Winkler, 2012; Baer, Barger, Savoy, Serce, Tata, 2017)

Benchmark model (2012)



(Krippendorf, Nilles, Ratz, Winkler, 2012)

Conclusion

Discrete symmetries are absolutely crucial ingredients for particle physics models.

- Traditional discrete symmetries are relevant for
  - flavour symmetries
  - hierarchies of Yukawa couplings
  - accidental Peccei-Quinn symmetry
- Discrete $R-$symmetries are important for
  - μ problem and Minkowski vacuum
  - the question of proton stability and stable LSP
  - pattern of soft terms for "Natural Susy".

Origin from geometry and geography of extra dimensions.
A challenge for string theory model building.