Heterotic Brane World

Hans Peter Nilles

Physikalisches Institut

Universität Bonn

Germany

Based on work with

S. Förste, O. Lebedev, S. Raby, S. Ramos-Sanchez, M. Ratz, P. Vaudrevange

and A. Wingerter

For related work see:

Kobayashi, Raby, Zhang; Buchmüller, Hamaguchi, Lebedev, Ratz; Kim, Kyae

The road to the Standard Model

What do we want?

- gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- no chiral exotics

The road to the Standard Model

What do we want?

- gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- no chiral exotics

But there might be more:

- supersymmetry (SM extended to MSSM)
- neutrino masses (see-saw mechanism)

as a hint for a large mass scale around 10^{16} GeV

Grand Unification

SUSY-GUTs provide us with nice things like

- unified multiplets (e.g. spinors of SO(10))
- gauge coupling unification
- Yukawa unification
- neutrino see-saw (especially in SO(10))

Grand Unification

SUSY-GUTs provide us with nice things like

- unified multiplets (e.g. spinors of SO(10))
- gauge coupling unification
- Yukawa unification
- neutrino see-saw (especially in SO(10))

But there remain a few questions:

- breakdown of GUT group (large representations)
- doublet-triplet splitting problem (incomplete multiplets)
- proton stability (need for R-parity)

Local Grand Unification

Can such things come from string theory where it is notoriously difficult to obtain large representations (beyond the adjoint representation of the gauge group)?

Local Grand Unification

Can such things come from string theory where it is notoriously difficult to obtain large representations (beyond the adjoint representation of the gauge group)?

In fact string theory gives us a variant of GUTs

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

in a geometrical set-up known as local GUTs, realized in the framework of the “heterotic braneworld”.

Search strategy

We adopt a strategy

- based on a top-down approach

where we use geometrical intuition to incorporate

- those aspects of grand unification that seem to be realized in nature

Search strategy

We adopt a strategy

- based on a top-down approach

where we use geometrical intuition to incorporate

- those aspects of grand unification that seem to be realized in nature

Main message

- local GUTs can be incorporated in string theory
- many aspects of MSSM depend on geometry of extra dimensions

We seem to live at a very special point in moduli space!

Outline

- orbifold compactification and its geometrical interpretation as heterotic braneworld
- a $Z_2 \times Z_2$ toy scenario exhibiting the "power of geometry"
- GUTs without GUT group
- a benchmark scenario based on the $Z_6 II$ orbifold
- scan of the landscape of the benchmark scenario
- road to realistic model building
- explicit models (see talk of M.Ratz)
- summary and outlook

Heterotic Brane World

Fields can propagate

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

Heterotic Brane World

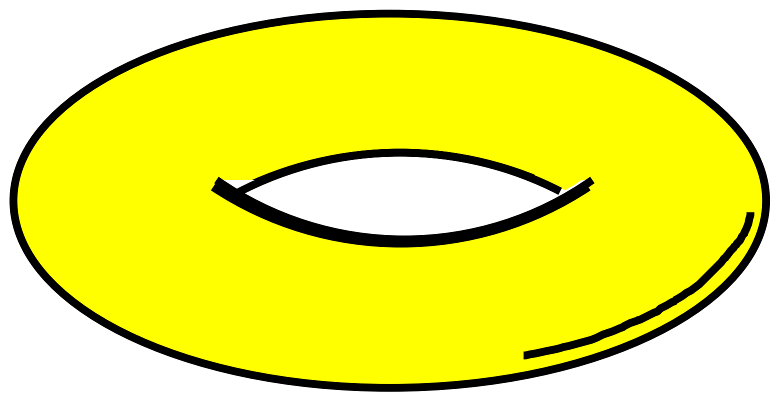
Fields can propagate

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

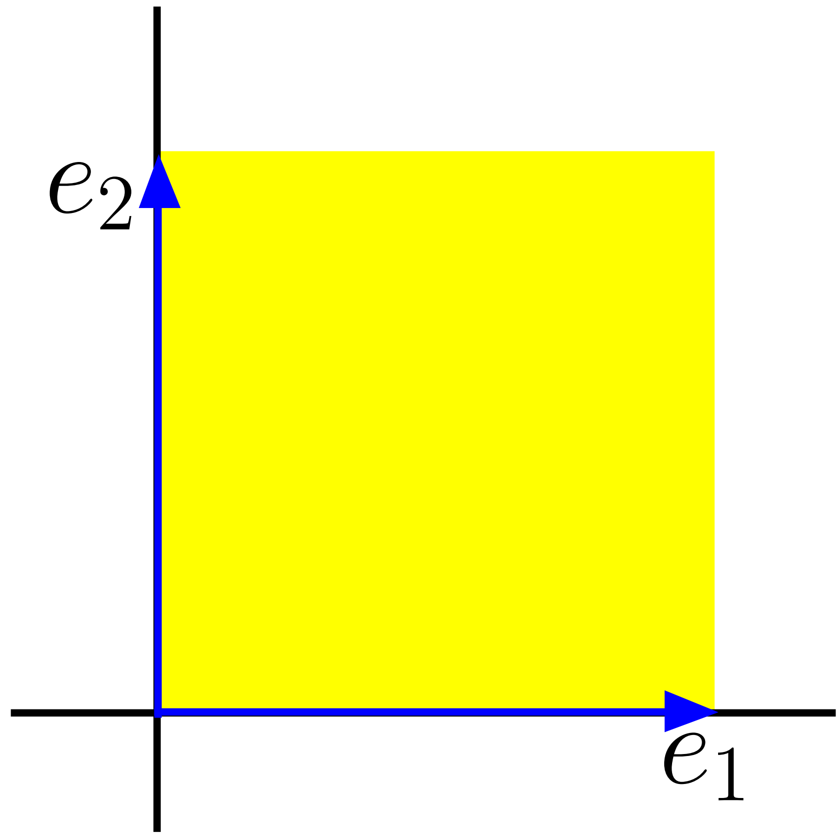
Orbifold compactifications of the heterotic string combine

- calculability of torus compactification
- with a simple and intuitive geometrical interpretation.
- possible extension to CY-compactification in the presence of “thick branes” (blow up)

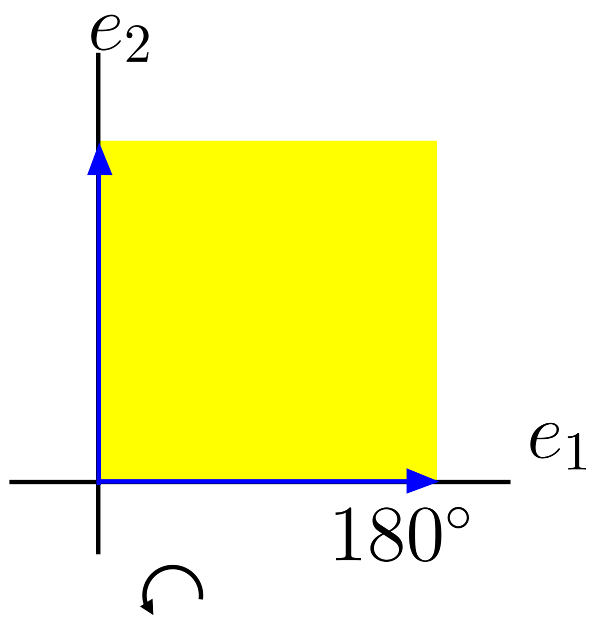
Torus T_2



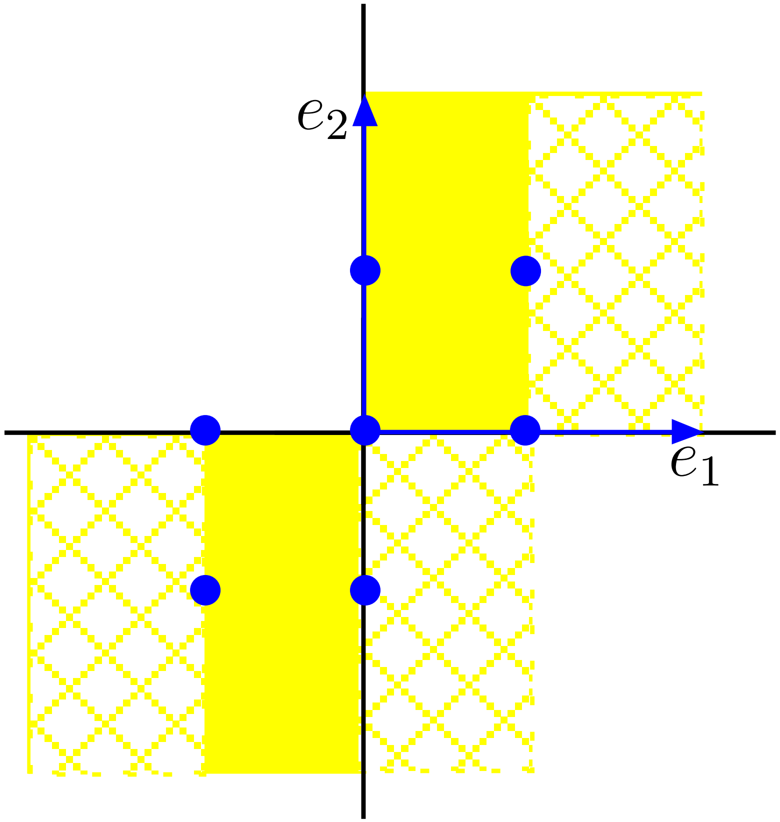
Torus T_2



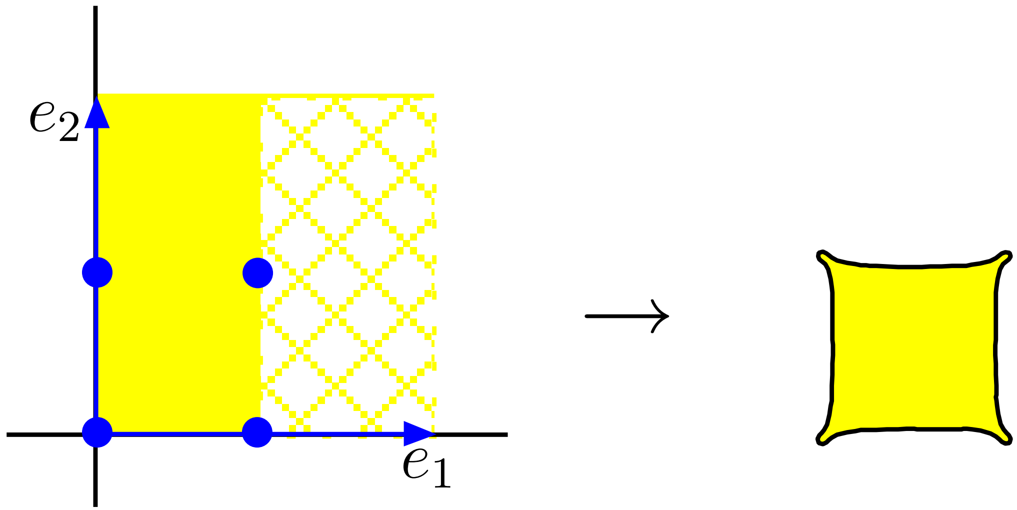
A Z_2 twist



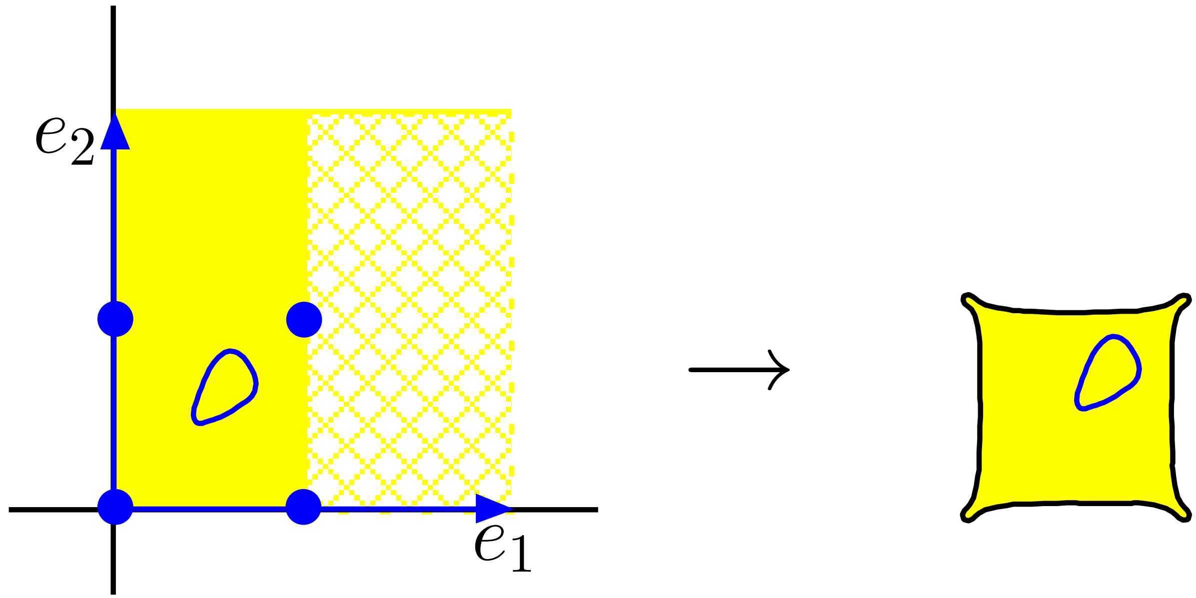
Orbifolding



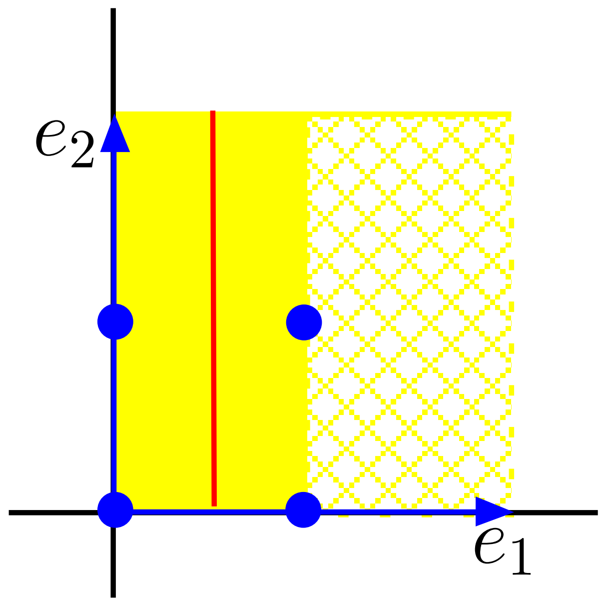
Ravioli

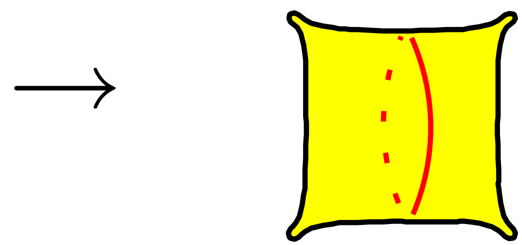


Bulk Modes

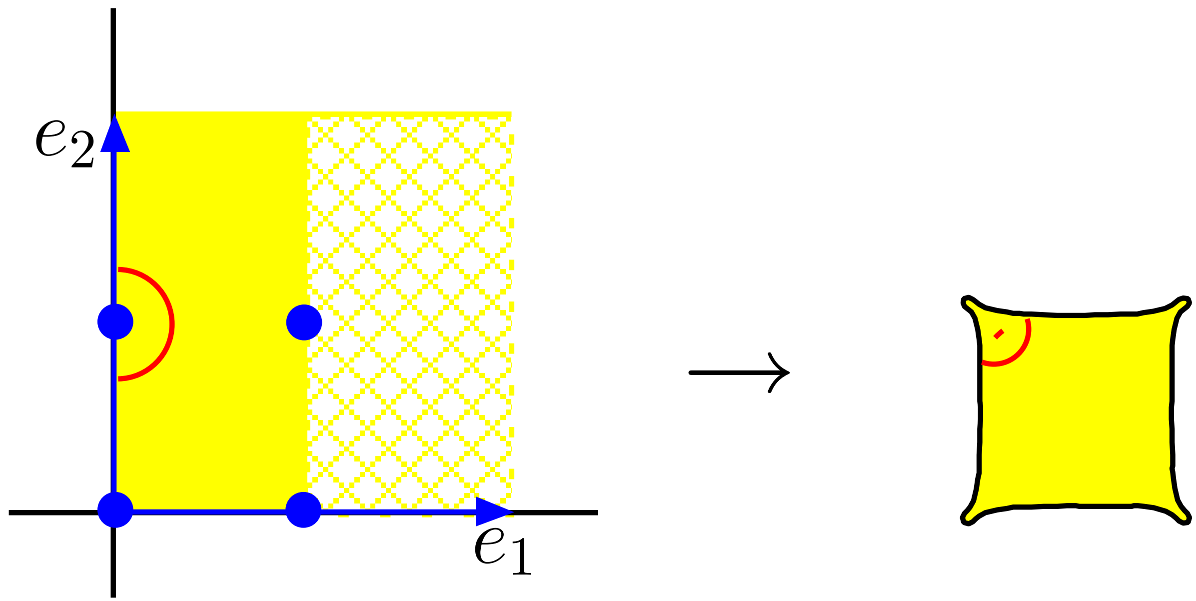


Winding Modes

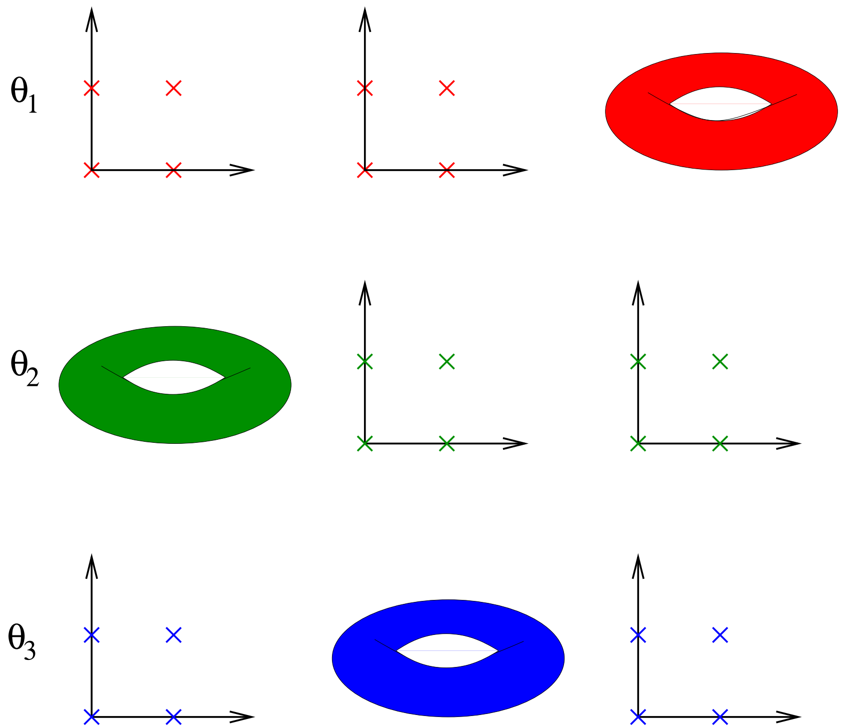




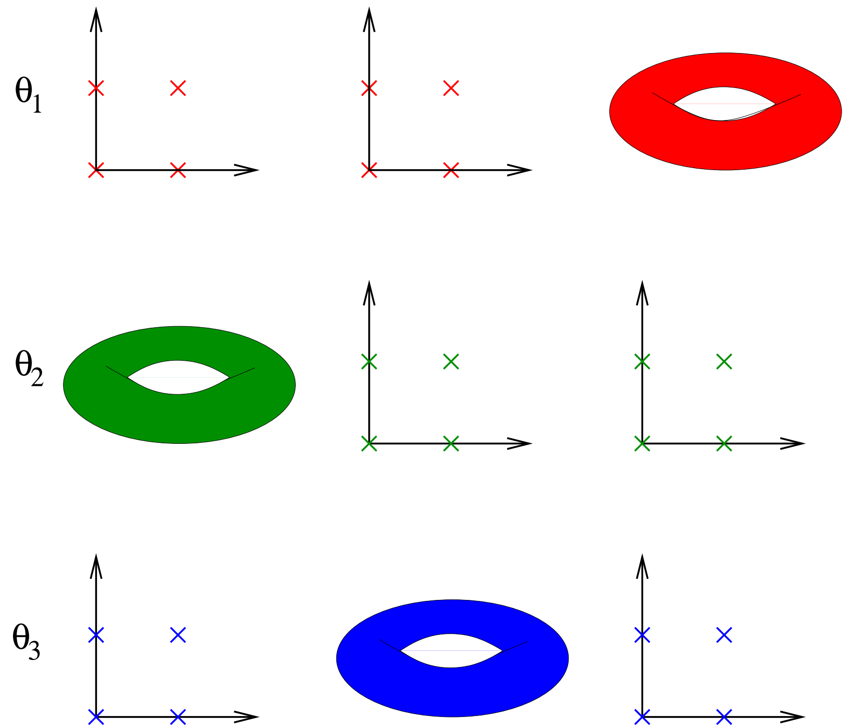
Brane Modes



$\mathbb{Z}_2 \times \mathbb{Z}_2$ Example

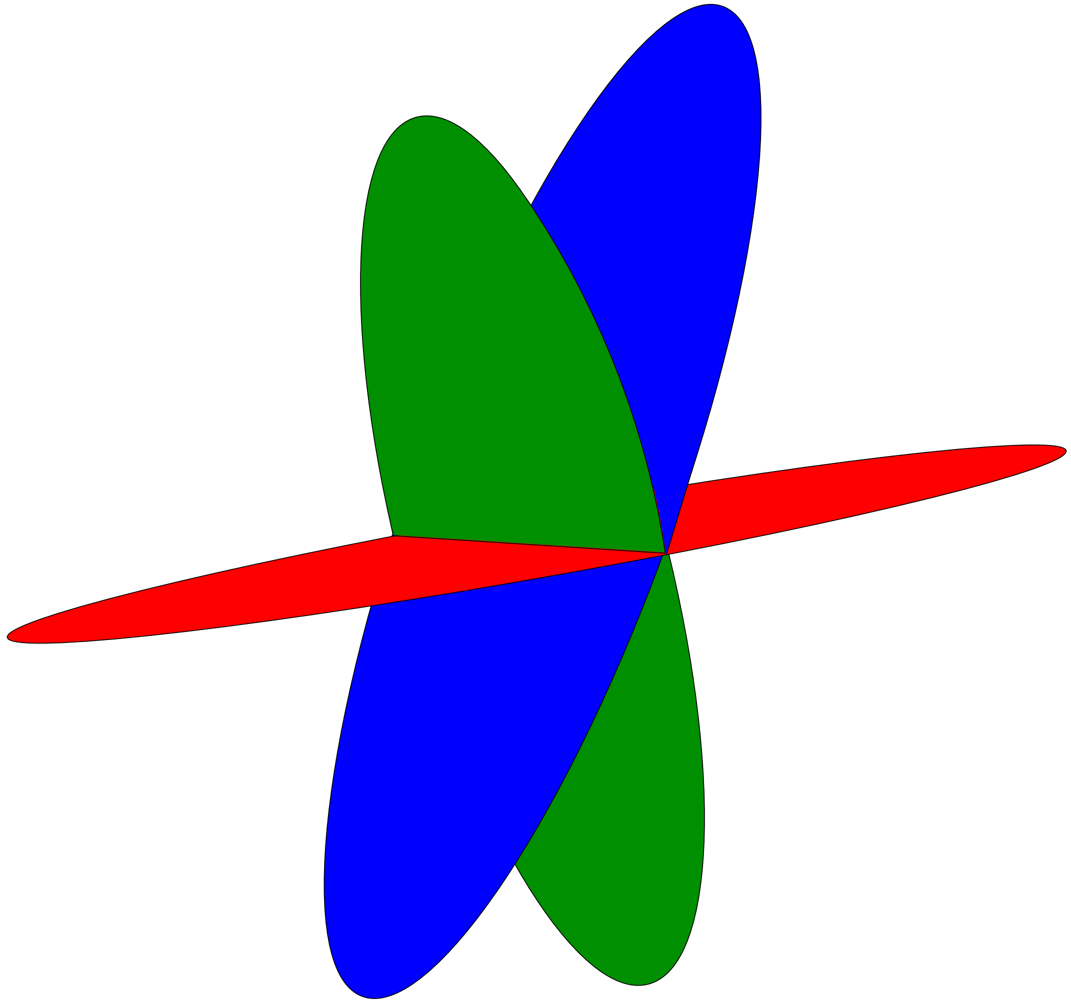


$\mathbb{Z}_2 \times \mathbb{Z}_2$ Example

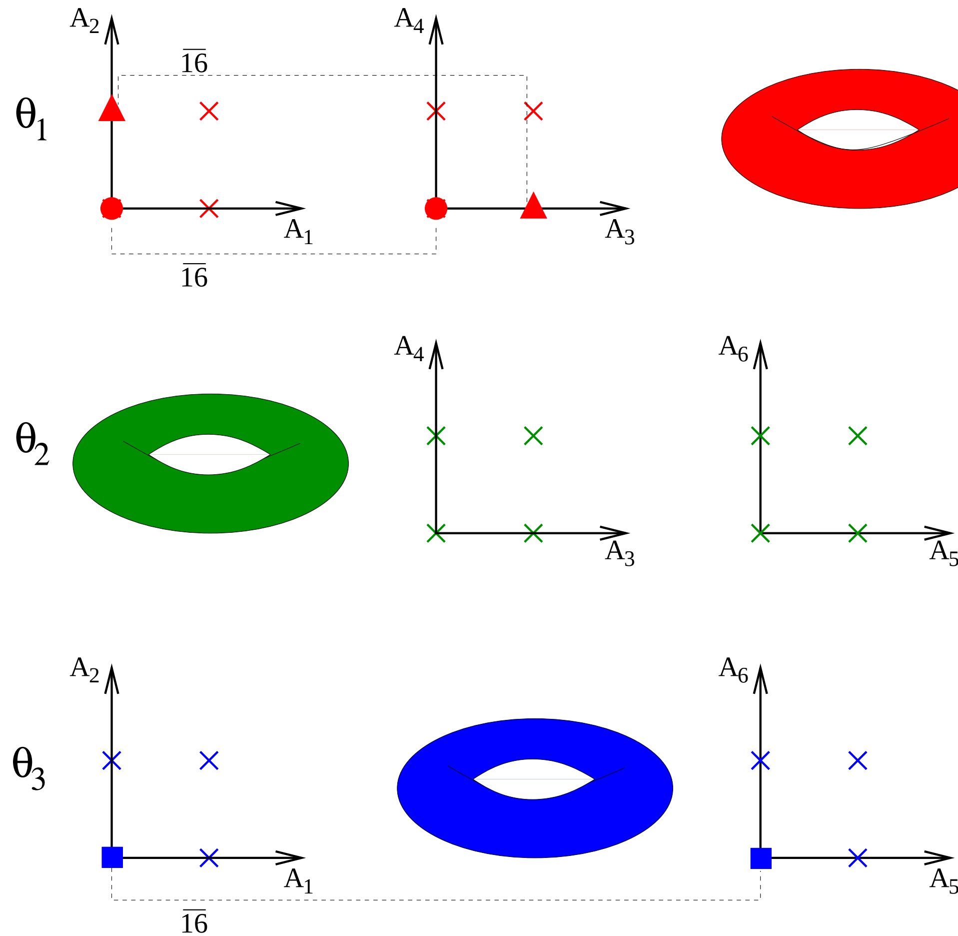


3 twisted sectors (with 16 fixed tori in each) lead to a geometrical picture of ....

Intersecting Branes

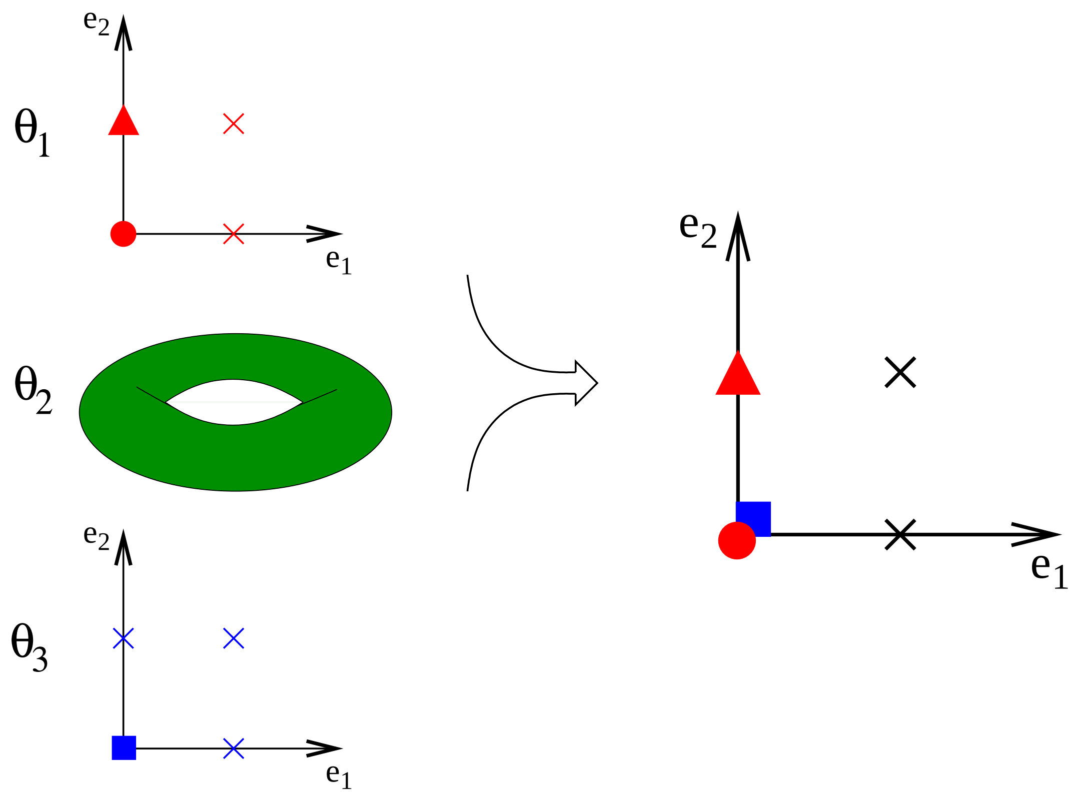


Three family $SO(10)$ toy model



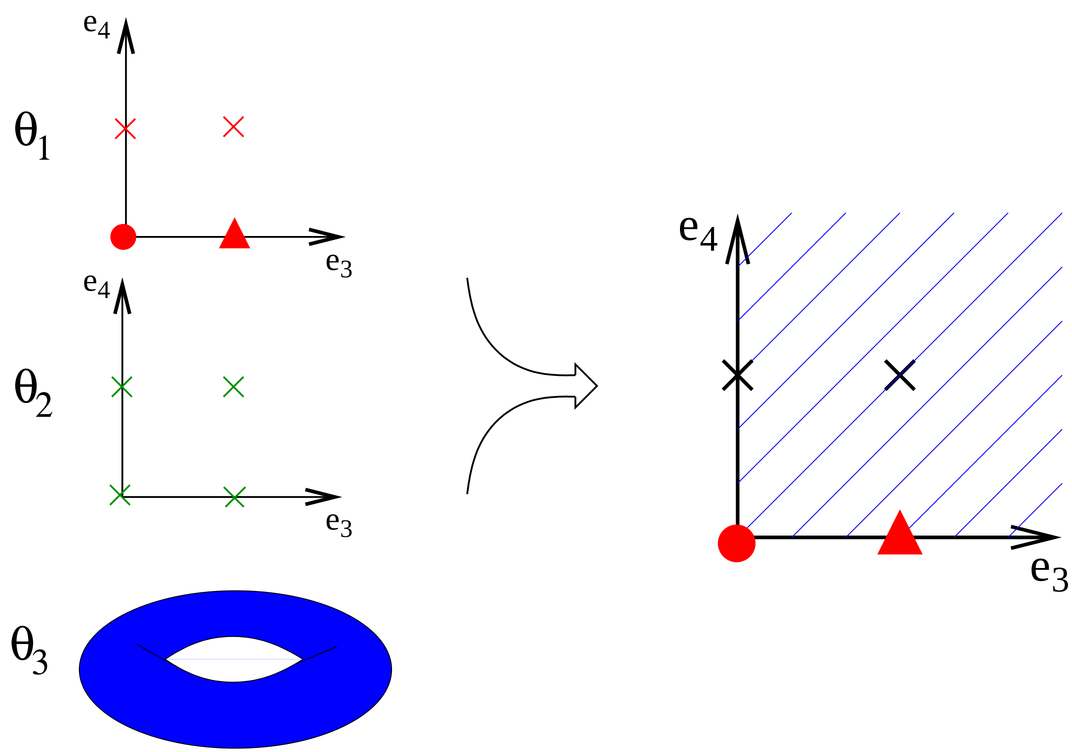
(Förste, HPN, Vaudrevange, Wingerter, 2004)

Zoom on first torus ...



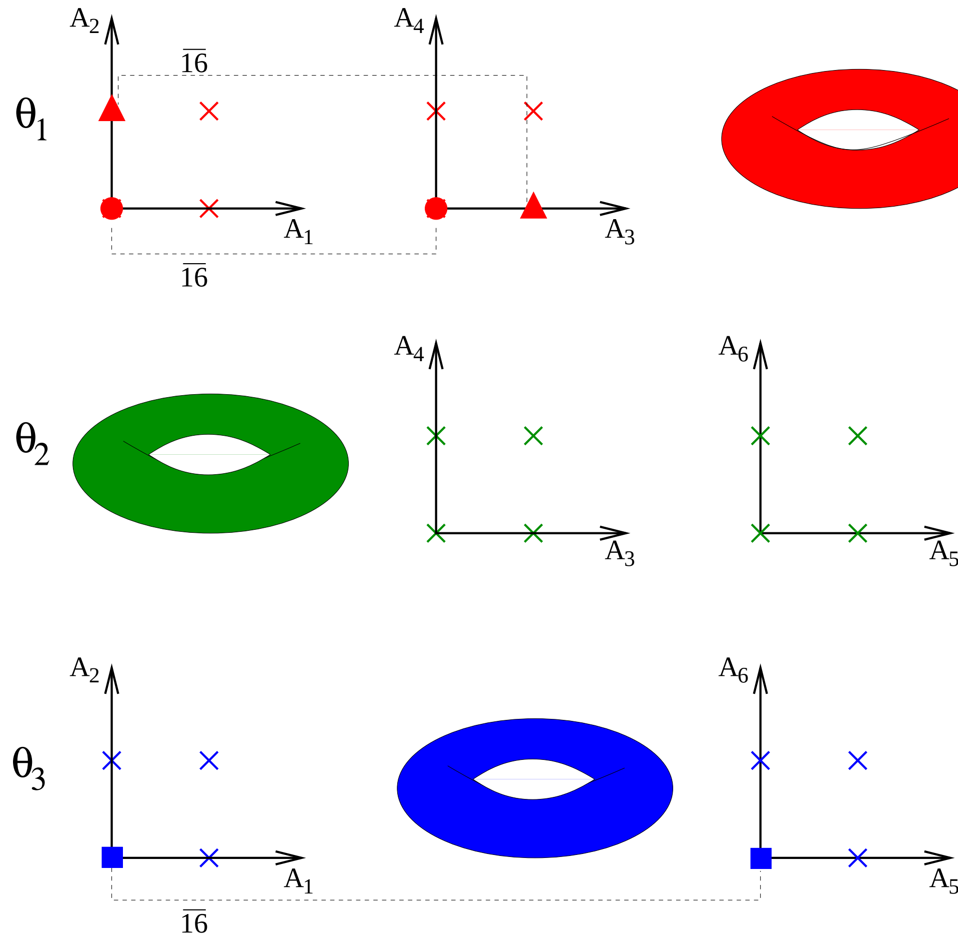
Interpretation as 6-dim. model with 3 families on branes

second torus ...



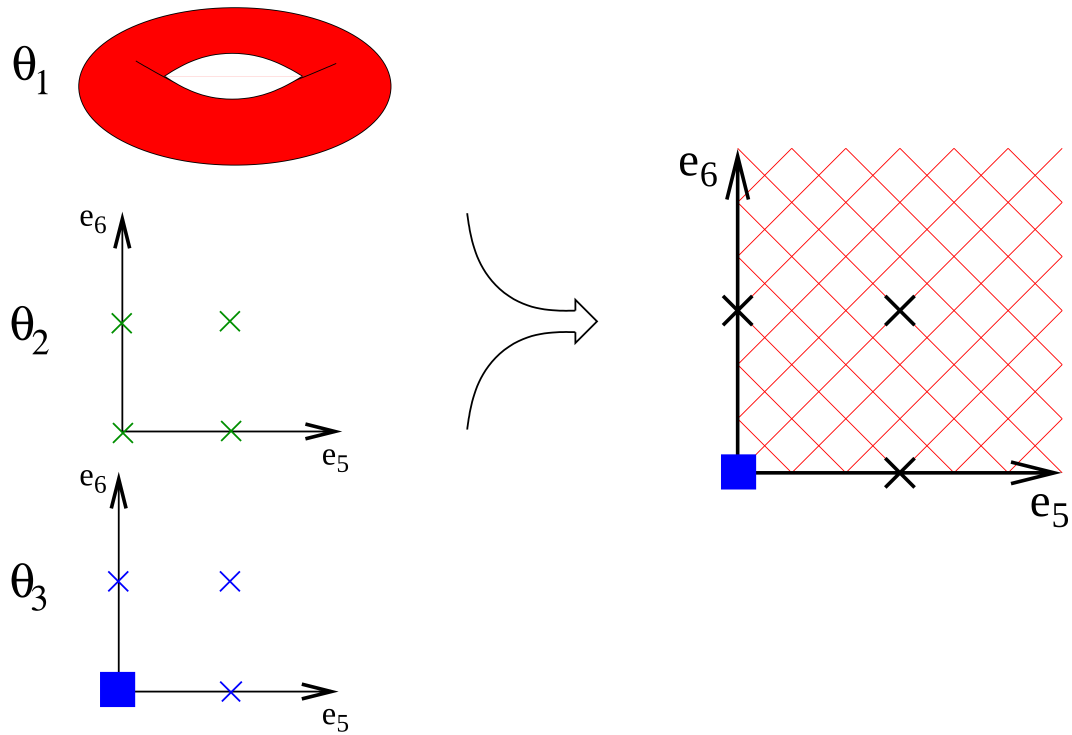
... 2 families on branes, one in (6d) bulk ...

Three family $SO(10)$ toy model



Localization of families at various fixed tori

third torus



... 1 family on brane, two in (6d) bulk.

Localization

Quarks, Leptons and Higgs fields can live:

- 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)

Localization

Quarks, Leptons and Higgs fields can live:

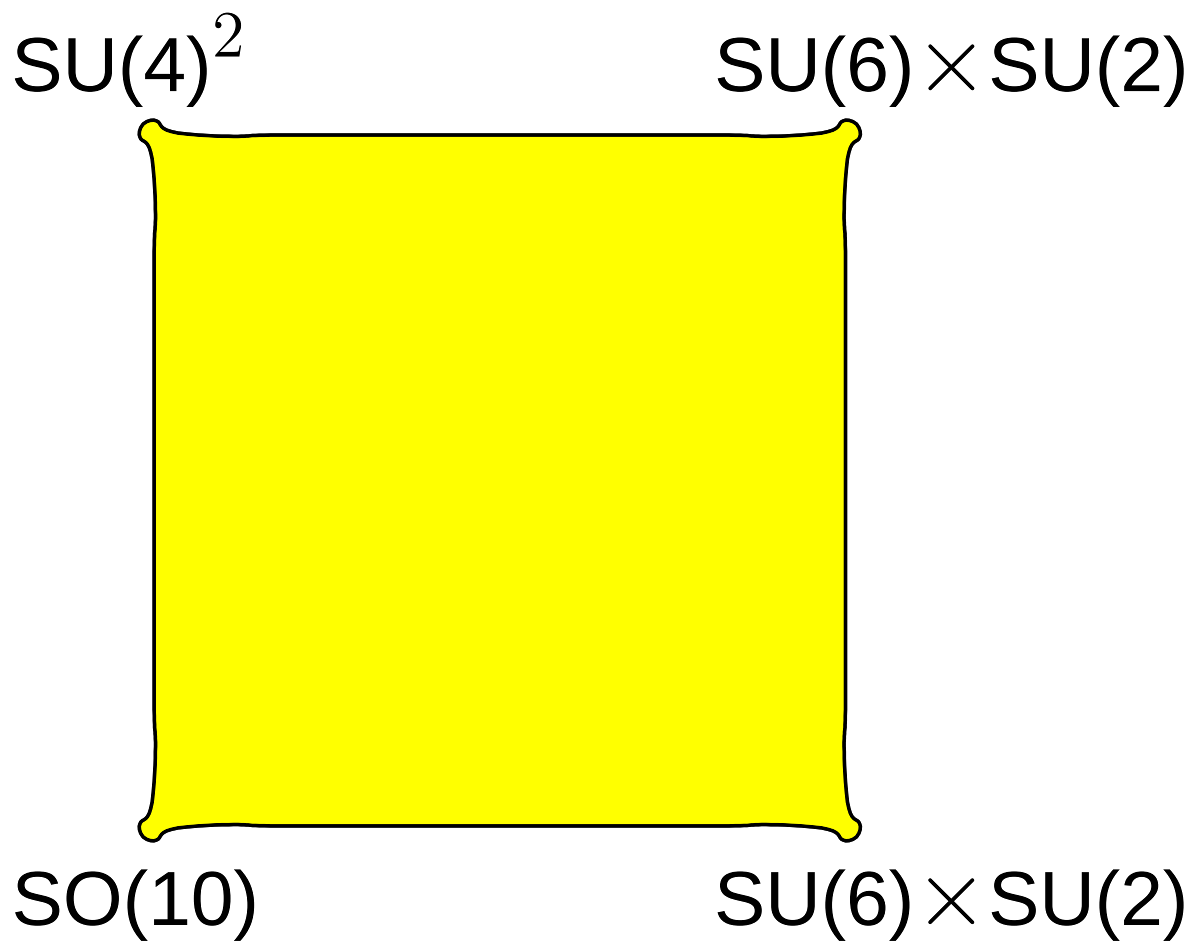
- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

but there is also a “localization” of gauge fields

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

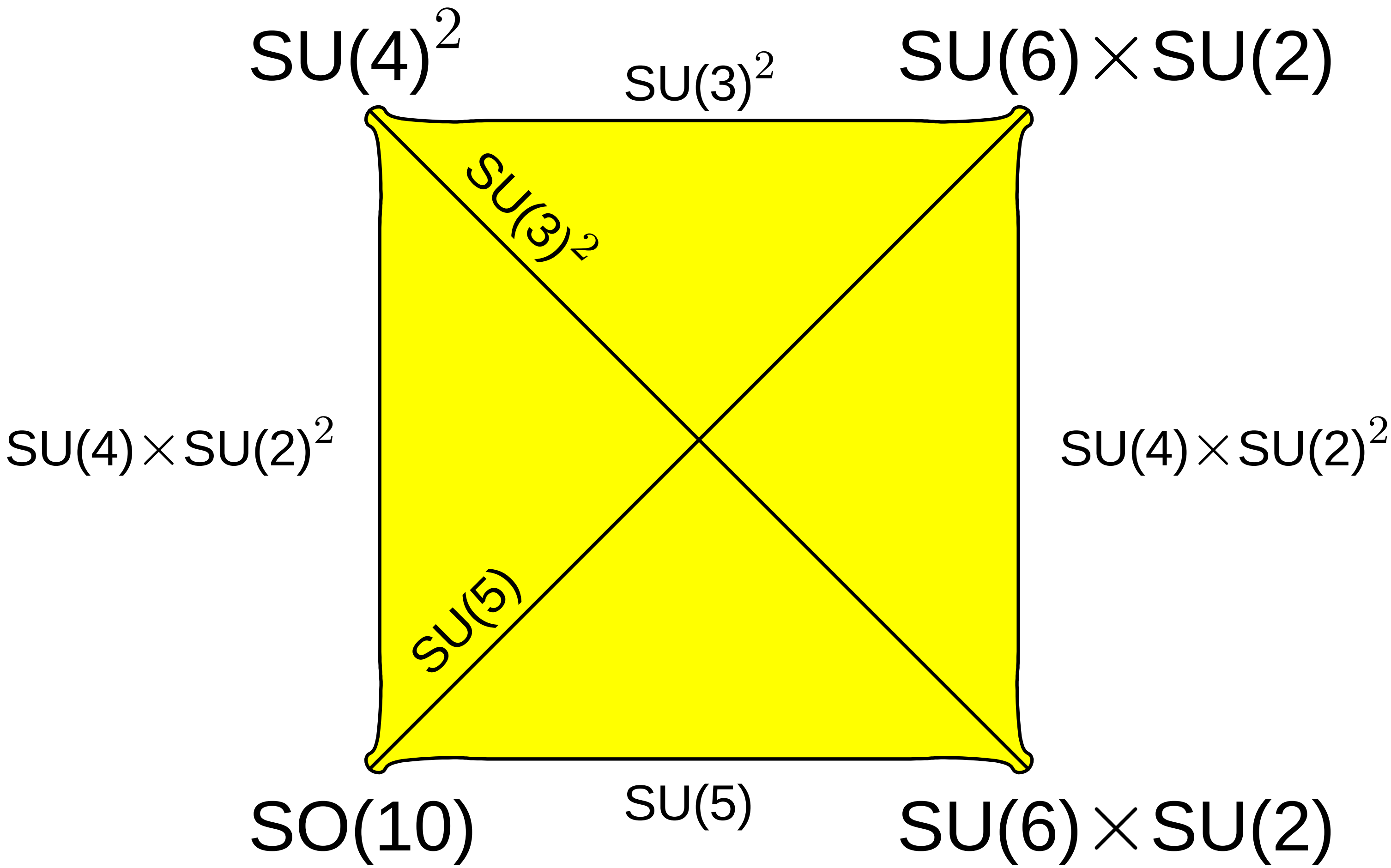
Observed 4-dimensional gauge group is common subroup of the various localized gauge groups!

Localized Gauge Symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



The Memory of SO(10)

- $SO(10)$ is realized in the higher dimensional theory
- broken in $d = 4$
- complete and incomplete multiplets

The Memory of SO(10)

- $SO(10)$ is realized in the higher dimensional theory
- broken in $d = 4$
- complete and incomplete multiplets

Still there could be remnants of $SO(10)$ symmetry

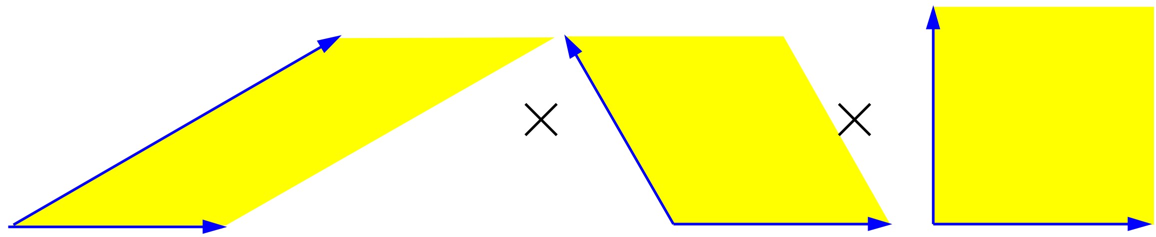
- 16 of SO(10) at some branes
- correct hypercharge normalization
- R-parity

that are very useful for realistic model building ...

Unification

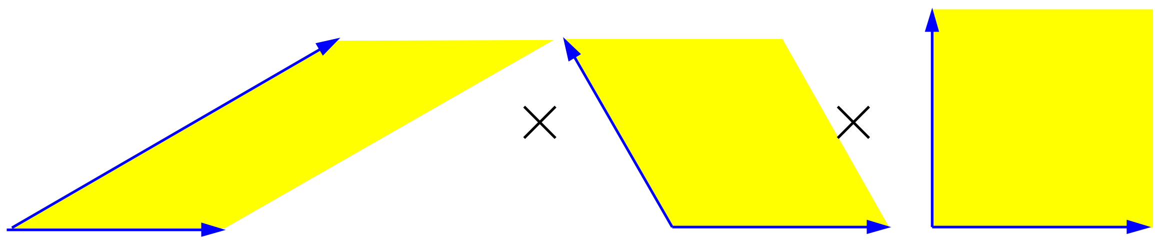
- SO(10) memory provides a reasonable value of $\sin^2\theta_W$ and a unified definition of hypercharge
- presence of fixed tori allows for large threshold corrections at the high scale to match string and unification scale
- gauge-Yukawa unification from SO(10) memory for some families (on an SO(10) brane)
- no gauge-Yukawa unification for other families required

Benchmark Scenario: Z_6 II orbifold



(Kobayashi, Raby, Zhang, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

Benchmark Scenario: Z_6 II orbifold



(Kobayashi, Raby, Zhang, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

- provides fixed points and fixed tori
- allows for 61 different shifts out of which 2 lead to $SO(10)$ gauge group
- allows for localized 16-plets for 2 families
- $SO(10)$ broken via Wilson lines
- nontrivial hidden sector gauge group

Selection Strategy

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$
② models with 2 Wilson lines	$22,000$	$7,800$
③ SM gauge group $\subset$ SO(10)	3563	1163
④ 3 net $(\mathbf{3},\mathbf{2})$	1170	492
⑤ non–anomalous $\mathrm{U}(1)_Y \subset \mathrm{SU}(5)$	528	234
⑥ 3 generations $+$ vector-like	128	90

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

Decoupling of exotics

requires extensive technical work:

- analysis of Yukawa couplings $S^n E\bar{E}$
- vevs of S break additional $U(1)$ symmetries
- our analysis includes $n \leq 6$

Decoupling of exotics

requires extensive technical work:

- analysis of Yukawa couplings $S^n E\bar{E}$
- vevs of S break additional $U(1)$ symmetries
- our analysis includes $n \leq 6$

Requirement of D-flatness

- vevs of S should not break supersymmetry
- anomalous U(1)'s and Fayet-Iliopoulos terms
- checking D-flatness with method of gauge invariant monomials

MSSM candidates

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$
③ SM gauge group $\subset$ SO(10)	3563	1163
④ 3 net $(\mathbf{3},\mathbf{2})$	1170	492
⑤ non–anomalous $\mathrm{U}(1)_Y \subset \mathrm{SU}(5)$	528	234
⑥ 3 generations $+$ vector-like	128	90
⑦ exotics decouple	106	85
⑧ D-flat solutions	105	85

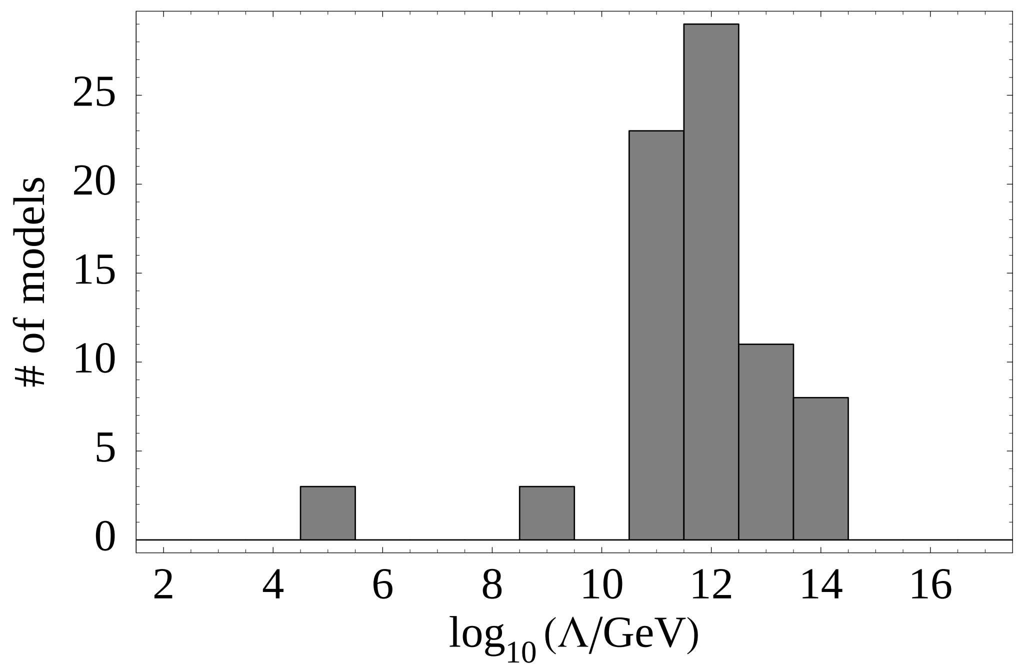
(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, to appear)

Road to the MSSM

We thus have constructed 190 models with the exact spectrum of the MSSM (+ decoupled hidden sector) and we can now analyze more detailed properties like:

- gauge- and Yukawa unification
- proton stability (B-L, R-parity....)
- see saw mechanism for neutrino masses
- origin of μ term
- axion candidates
- discrete family symmetries
- hidden sector supersymmetry breakdown

Hidden Sector Susy Breakdown



$m_{3/2} = \Lambda^3/M^2_{\rm Planck}$ (with $\Lambda = \mu \exp(-1/g^2_{\rm hidden}(\mu))$)
from hidden sector gaugino condensation

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

Conclusion

Our benchmark scenario leads to

- 190 models with the exact spectrum of the MSSM (absence of chiral exotics)
- local grand unification
- gauge- and (partial) Yukawa unification
- examples of neutrino see-saw mechanism
- models with R-parity
- solution to the μ-problem
- hidden sector gaugino condensation

Conclusion

- strategy based on geometrical intuition is successful
- properties of models can trace back the geometry of extra dimensions
- heterotic versus Type II braneworld
  - bulk gauge group
  - complete chiral multiplets
  - chiral exotics
  - R-parity (B-L and seesaw mechanism)
- localization of fields at various “corners” of Calabi-Yau manifold
- remnants of Grand Unification indicate that we live in a special place of the compactified extra dimensions!