Grand Unification and Strings:
the Geography of Extra Dimensions

Hans Peter Nilles

Physikalisches Institut, Universität Bonn

Based on work with S. Förste, P. Vaudrevange and A. Wingerter

hep-th/0406208, hep-th0410160, hep-th/0504117

Outline

- Grand Unification
- GUTs without GUT group
- Spinors of SO(10)
- An SO(10) Model with 3 Families
- Gauge group geography in extra dimensions
- Unification ($\sin^2\theta_W$)
- Proton decay
- Yukawa textures and flavour symmetries
- Electroweak symmetry breakdown
- Outlook

Bottom-up input

Experimental findings suggest the existence of two new scales of physics beyond the standard model $M_{\mathrm{GUT}} \sim 10^{16}\mathrm{GeV}$ (and $M_{\mathrm{SUSY}} \sim 10^{3}\mathrm{GeV}$):

Bottom-up input

Experimental findings suggest the existence of two new scales of physics beyond the standard model $M_{\mathrm{GUT}} \sim 10^{16}\mathrm{GeV}$ (and $M_{\mathrm{SUSY}} \sim 10^{3}\mathrm{GeV}$):

- Neutrino-oscillations and "See-Saw Mechanismus"
  $m_\nu \sim M_W^2/M_{\mathrm{GUT}}$
  $m_\nu \sim 10^{-3}\mathrm{eV}$ for $M_W \sim 100\mathrm{GeV}$,

Bottom-up input

Experimental findings suggest the existence of two new scales of physics beyond the standard model $M_{\mathrm{GUT}} \sim 10^{16}\mathrm{GeV}$ (and $M_{\mathrm{SUSY}} \sim 10^{3}\mathrm{GeV}$):

- Neutrino-oscillations and “See-Saw Mechanismus”
  $m_\nu \sim M_W^2/M_{\mathrm{GUT}}$
  $m_\nu \sim 10^{-3}\mathrm{eV}$ for $M_W \sim 100\mathrm{GeV}$,

- Evolution of couplings constants of the standard model towards higher energies.

Bottom-up input

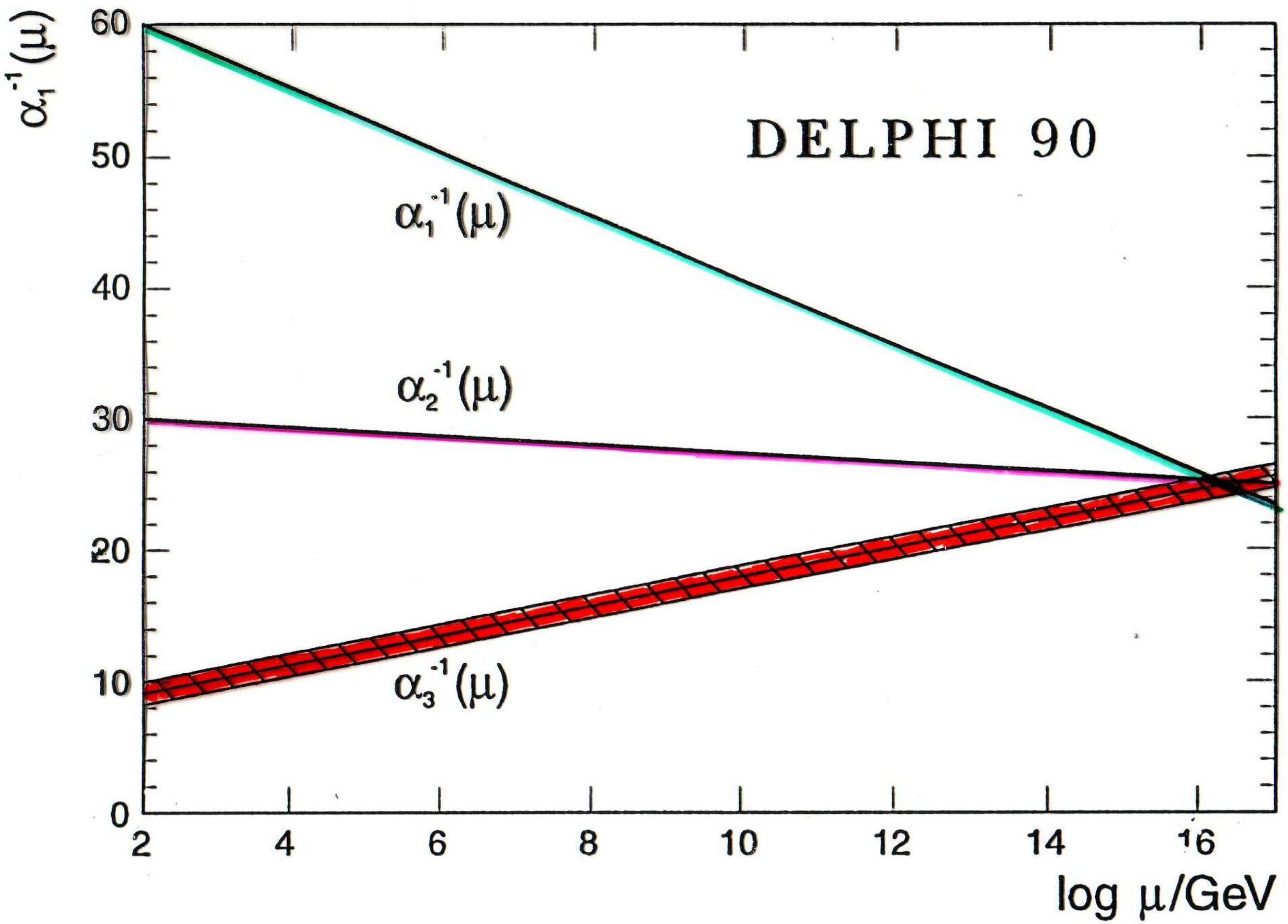
Experimental findings suggest the existence of two new scales of physics beyond the standard model $M_{\mathrm{GUT}} \sim 10^{16}\mathrm{GeV}$ (and $M_{\mathrm{SUSY}} \sim 10^{3}\mathrm{GeV}$):

- Neutrino-oscillations and “See-Saw Mechanismus”
  $m_\nu \sim M_W^2/M_{\mathrm{GUT}}$
  $m_\nu \sim 10^{-3}\mathrm{eV}$ for $M_W \sim 100\mathrm{GeV}$,

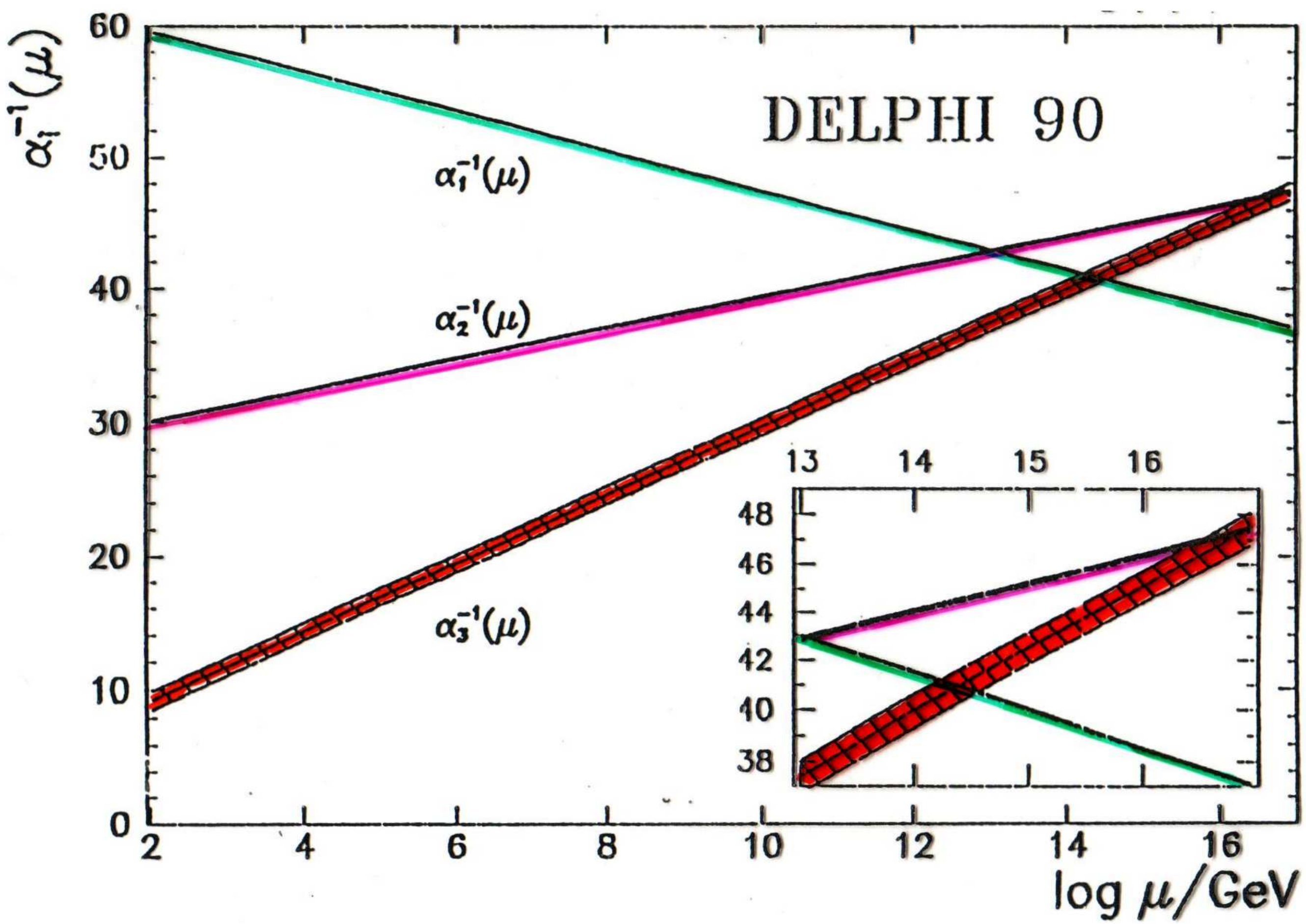
- Evolution of couplings constants of the standard model towards higher energies.

Does this fit in the “Landscape” of string theory?

MSSM (supersymmetric)



Standard Model



Grand Unification

has changed our view of the world,
but there are also some problematic aspects of the grand unified picture.

Grand Unification

has changed our view of the world,
but there are also some problematic aspects of the grand unified picture.

Most notably

- absence of proton decay
- doublet - triplet splitting
- complicated Higgs sector to break grand unified gauge group spontaneously

Grand Unification

has changed our view of the world,
but there are also some problematic aspects of the grand unified picture.

Most notably

- absence of proton decay
- doublet - triplet splitting
- complicated Higgs sector to break grand unified gauge group spontaneously

Can we avoid these problems in a more complete theory?

String theory candidates

In ten space-time dimensions.....

- Type I SO(32)
- Type II orientifolds
- Heterotic SO(32)
- Heterotic $E_8 \times E_8$
- Intersecting Branes $U(N)^M$

String theory candidates

In ten space-time dimensions.....

- Type I SO(32)
- Type II orientifolds
- Heterotic SO(32)
- Heterotic $E_8 \times E_8$
- Intersecting Branes $U(N)^M$

....or in eleven

- Horava-Witten heterotic M-theory
- Type IIA on manifolds with G_2 holonomy

Orbifolds

Orbifold compactifications combine the

- success of Calabi-Yau compactification
- calculability of torus compactification

Orbifolds

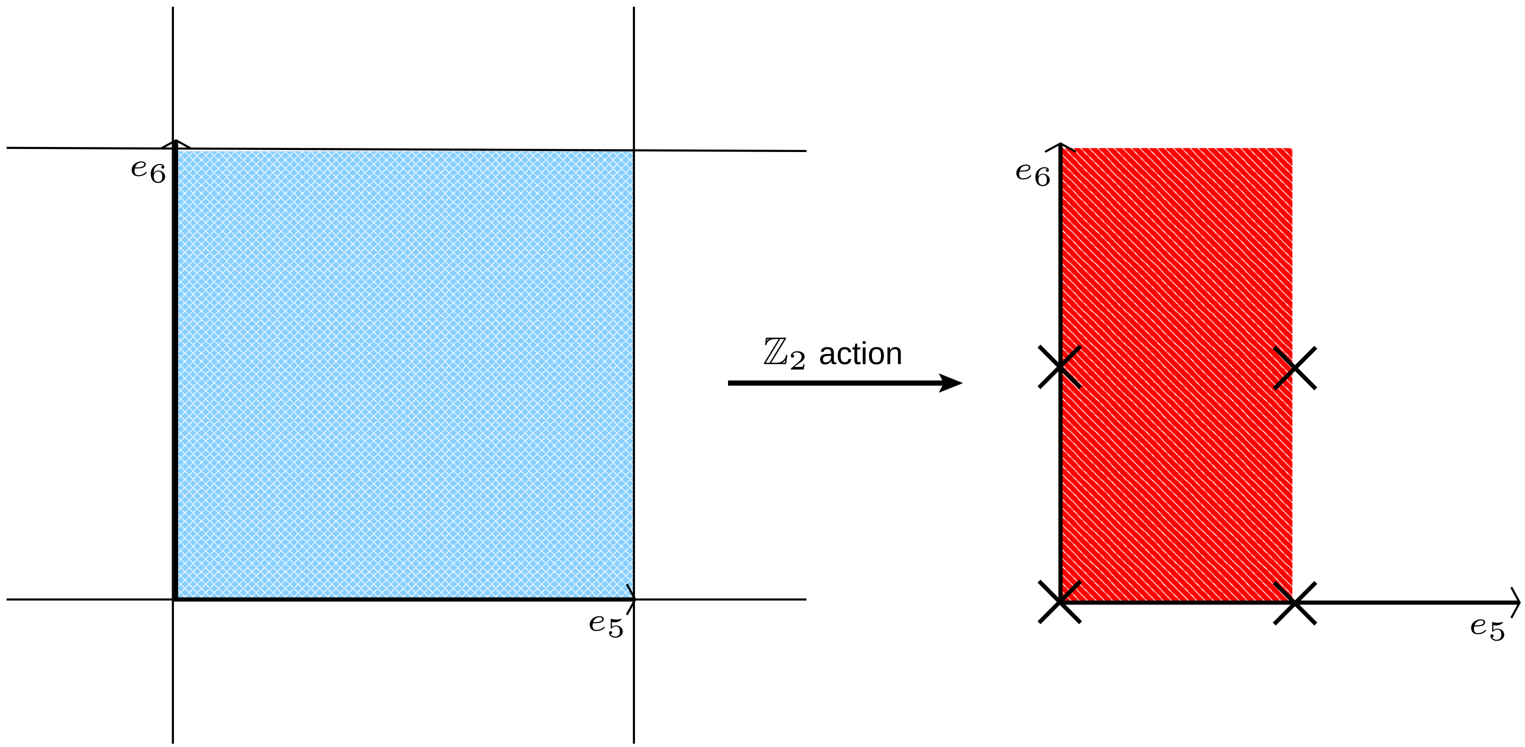
Orbifold compactifications combine the

- success of Calabi-Yau compactification
- calculability of torus compactification

In case of the heterotic string fields can propagate

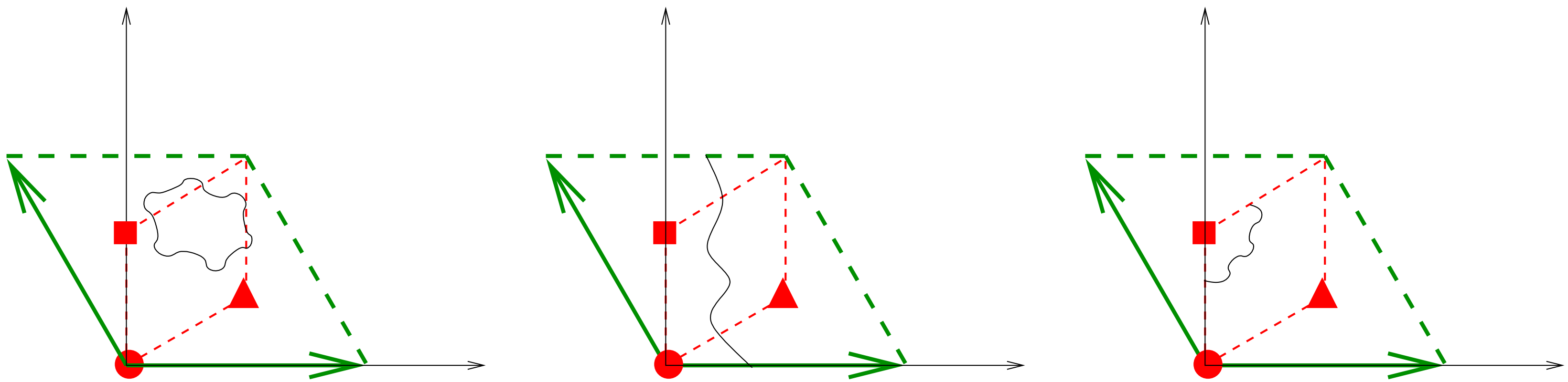
- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

$\mathbb{Z}_2$ Example

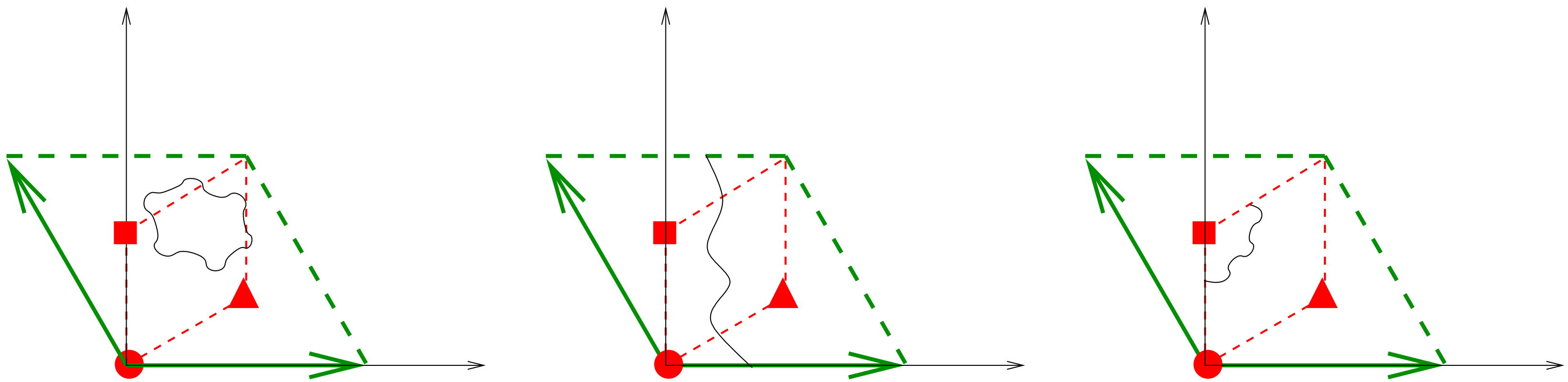


The geometry of the $\mathbb{Z}_2$ orbifold.

$\mathbb{Z}_3$ Example



$\mathbb{Z}_3$ Example



- Action of the space group on coordinates

$$X^i \rightarrow (\theta^k X)^i + n_\alpha e^i_\alpha, \quad k = 0, 1, 2, \quad i, \alpha = 1, \ldots, 6$$

- Embed twist in gauge degrees of freedom

$$X^I \rightarrow (\Theta^k X)^I \quad I = 1, \ldots, 16$$

Classification of $\mathbb{Z}_3$ Orbifold

Very few inequivalent models

Classification of $\mathbb{Z}_3$ Orbifold

Very few inequivalent models

Case	Shift V	Gauge Group	Gen.
1	$\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)\left(0^8\right)$	$\mathsf{E}_6\times\mathsf{SU}(3)\times\mathsf{E}_8'$	36
2	$\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)$	$\mathsf{E}_6\times\mathsf{SU}(3)\times\mathsf{E}_6'\times\mathsf{SU}(3)'$	9
3	$\left(\frac{1}{3},\frac{1}{3},0^6\right)\left(\frac{2}{3},0^7\right)$	$\mathsf{E}_7\times\mathsf{U}(1)\times\mathsf{SO}(14)'\times\mathsf{U}(1)'$	0
4	$\left(\frac{1}{3},\frac{1}{3},\frac{1}{3},\frac{1}{3},\frac{2}{3},0^3\right)\left(\frac{2}{3},0^7\right)$	$\mathsf{SU}(9)\times\mathsf{SO}(14)'\times\mathsf{U}(1)'$	9

Classification of $\mathbb{Z}_3$ Orbifold

Very few inequivalent models

Case	Shift V	Gauge Group	Gen.
1	$\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)\left(0^8\right)$	$\mathsf{E}_6\times\mathsf{SU}(3)\times\mathsf{E}_8'$	36
2	$\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)$	$\mathsf{E}_6\times\mathsf{SU}(3)\times\mathsf{E}_6'\times\mathsf{SU}(3)'$	9
3	$\left(\frac{1}{3},\frac{1}{3},0^6\right)\left(\frac{2}{3},0^7\right)$	$\mathsf{E}_7\times\mathsf{U}(1)\times\mathsf{SO}(14)'\times\mathsf{U}(1)'$	0
4	$\left(\frac{1}{3},\frac{1}{3},\frac{1}{3},\frac{1}{3},\frac{2}{3},0^3\right)\left(\frac{2}{3},0^7\right)$	$\mathsf{SU}(9)\times\mathsf{SO}(14)'\times\mathsf{U}(1)'$	9

as a result of the degeneracy of the matter multiplets at the 27 fixed points

Classification of $\mathbb{Z}_3$ Orbifold

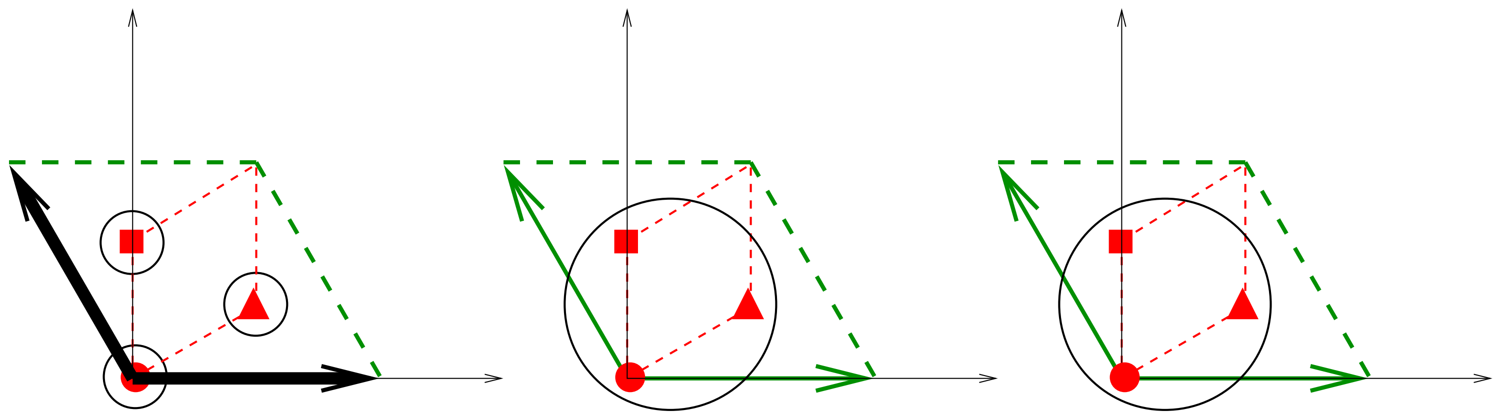
Very few inequivalent models

Case	Shift V	Gauge Group	Gen.
1	$\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)\,\left(0^8\right)$	$\mathrm{E}_6\times\mathrm{SU}(3)\times\mathrm{E}_8'$	36
2	$\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)\,\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)$	$\mathrm{E}_6\times\mathrm{SU}(3)\times\mathrm{E}_6'\times\mathrm{SU}(3)'$	9
3	$\left(\frac{1}{3},\frac{1}{3},0^6\right)\,\left(\frac{2}{3},0^7\right)$	$\mathrm{E}_7\times\mathrm{U}(1)\times\mathrm{SO}(14)'\times\mathrm{U}(1)'$	0
4	$\left(\frac{1}{3},\frac{1}{3},\frac{1}{3},\frac{1}{3},\frac{2}{3},0^3\right)\,\left(\frac{2}{3},0^7\right)$	$\mathrm{SU}(9)\times\mathrm{SO}(14)'\times\mathrm{U}(1)'$	9

as a result of the degeneracy of the matter multiplets at the 27 fixed points

We need to lift this degeneracy ...

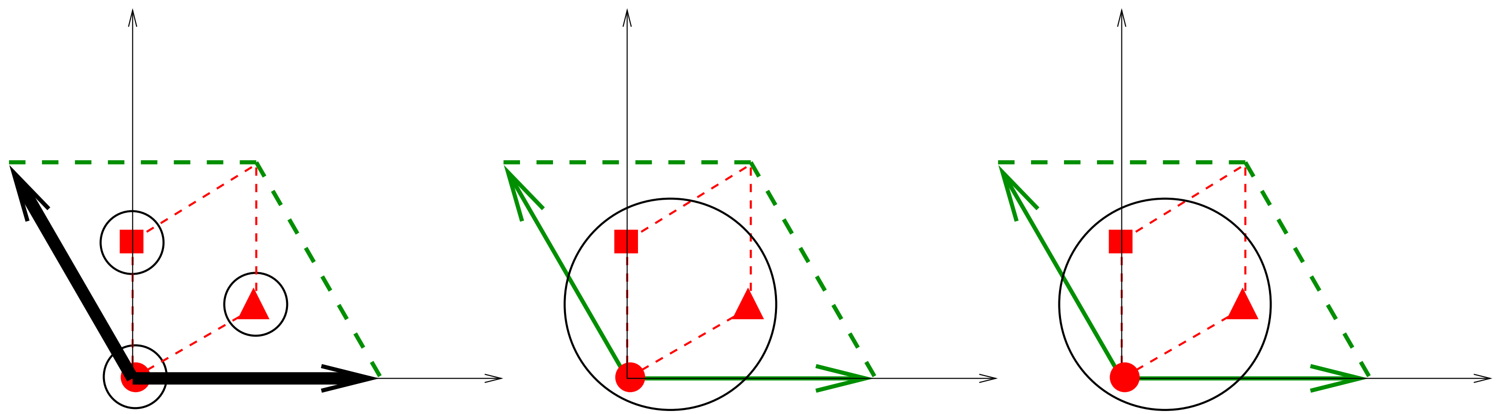
$\mathbb{Z}_3$ Orbifold with Wilson lines



Torus shifts embedded in gauge group as well

$$X^I \to X^I + V^I + n_\alpha A^I_\alpha$$

$\mathbb{Z}_3$ Orbifold with Wilson lines



Torus shifts embedded in gauge group as well

$$X^I \to X^I + V^I + n_\alpha A_\alpha^I$$

- further gauge symmetry breakdown
- number of generations reduced

Early work on the $\mathbb{Z}_3$ Orbifold

Successful model building with

- three families of quarks and leptons
- gauge group $SU(3) \times SU(2) \times U(1)^n$
- doublet-triplet splitting
- mechanism for Yukawa suppression
- absence of grand unified gauge bosons

Early work on the $\mathbb{Z}_3$ Orbifold

Successful model building with

- three families of quarks and leptons
- gauge group $SU(3) \times SU(2) \times U(1)^n$
- doublet-triplet splitting
- mechanism for Yukawa suppression
- absence of grand unified gauge bosons

Leads to a picture of “GUTs without GUT group”

- Incomplete gauge and Higgs multiplets
- Transparent geometric interpretation

Things to improve

For models with $SU(3) \times SU(2) \times U(1)$ gauge group, the $\mathbb{Z}_3$ orbifold example is too rigid

- only fixed points and no fixed tori
- no “normal” grand unified picture (like $SO(10)$)
- no large string threshold corrections
- problems with electroweak symmetry breakdown
- value of $\sin^2\theta_W \neq 3/8$

Things to improve

For models with $SU(3) \times SU(2) \times U(1)$ gauge group, the $\mathbb{Z}_3$ orbifold example is too rigid

- only fixed points and no fixed tori
- no “normal” grand unified picture (like $SO(10)$)
- no large string threshold corrections
- problems with electroweak symmetry breakdown
- value of $\sin^2\theta_W \neq 3/8$

A successful approach in the framework of the $\mathbb{Z}_3$-orbifold might be

- $SU(3)^3$ trinification (Choi, Kim, 2003; Kim, 2004)

Work in the 90's

- some continuation on orbifold constructions, though not very specific
- fermionic formulation of heterotic string with very specific (semi) realistic models
- Type IIB orientifolds
- D brane constructions
- intersecting branes

Work in the 90's

- some continuation on orbifold constructions, though not very specific
- fermionic formulation of heterotic string with very specific (semi) realistic models
- Type IIB orientifolds
- D brane constructions
- intersecting branes

This gives a vast variety of models, both

- with or without supersymmetry in $d = 4$ ....
- small or large compactified dimensions ....

Some basic observations

- Gauge couplings meet at $10^{16} - 10^{17}$ GeV in the framework of the Minimal Supersymmetric Standard Model (MSSM)

Some basic observations

- Gauge couplings meet at $10^{16} - 10^{17}$ GeV in the framework of the Minimal Supersymmetric Standard Model (MSSM)
- See-saw mechanism for neutrino sector favours the interpretation of a family of quarks and leptons as a 16 dimensional spinor representation of SO(10)

Some basic observations

- Gauge couplings meet at $10^{16} - 10^{17}$ GeV in the framework of the Minimal Supersymmetric Standard Model (MSSM)
- See-saw mechanism for neutrino sector favours the interpretation of a family of quarks and leptons as a 16 dimensional spinor representation of SO(10)
- Model building in field theoretic orbifold GUTs in 5 and 6 dimensions seems to lead to promising results

Some basic observations

- Gauge couplings meet at $10^{16} - 10^{17}$ GeV in the framework of the Minimal Supersymmetric Standard Model (MSSM)
- See-saw mechanism for neutrino sector favours the interpretation of a family of quarks and leptons as a 16 dimensional spinor representation of SO(10)
- Model building in field theoretic orbifold GUTs in 5 and 6 dimensions seems to lead to promising results

Can we incorporate this into a string theory description?

Five golden rules

- Family as spinor of SO(10)
- Incomplete multiplets
- $N = 1$ superymmetry in $d = 4$
- Repetition of families from geometry
- Discrete symmetries of stringy origin (HPN, 2004)

Five golden rules

- Family as spinor of SO(10)
- Incomplete multiplets
- $N = 1$ superymmetry in $d = 4$
- Repetition of families from geometry
- Discrete symmetries of stringy origin (HPN, 2004)

Such a scheme should

- incorporate the successful structures of $SO(10)$-GUTs
- avoid (some of) the problems

Five golden rules

- Family as spinor of SO(10)
- Incomplete multiplets
- $N = 1$ superymmetry in $d = 4$
- Repetition of families from geometry
- Discrete symmetries of stringy origin (HPN, 2004)

Such a scheme should

- incorporate the successful structures of $SO(10)$-GUTs
- avoid (some of) the problems

We need more general constructions to identify remnants of $SO(10)$ in string theory .....

Candidates

In ten space-time dimensions.....

- Type I SO(32)
- Type II orientifolds
- Heterotic SO(32)
- Heterotic $E_8 \times E_8$
- Intersecting Branes $U(N)^M$

Candidates

In ten space-time dimensions.....

- Type I SO(32)
- Type II orientifolds
- Heterotic SO(32)
- Heterotic $E_8 \times E_8$
- Intersecting Branes $U(N)^M$

....or in eleven

- Horava-Witten heterotic M-theory
- Type IIA on manifolds with G_2 holonomy

Remnants of $SO(10)$ symmetry

If we insist on the spinor representation of $SO(10)$ we are essentially

- left with heterotic $E_8 \times E_8$ or $SO(32)$
- go beyond the simple example of the Z_3 orbifold

Remnants of $SO(10)$ symmetry

If we insist on the spinor representation of $SO(10)$ we are essentially

- left with heterotic $E_8 \times E_8$ or $SO(32)$
- go beyond the simple example of the Z_3 orbifold

The Z_3 orbifold had fixed points but no fixed tori, leading to difficulties to

- incorporate a correctly normalized $U(1)$-hypercharge
- accomodate satisfactory Yukawa couplings

Remnants of $SO(10)$ symmetry

If we insist on the spinor representation of $SO(10)$ we are essentially

- left with heterotic $E_8 \times E_8$ or $SO(32)$
- go beyond the simple example of the Z_3 orbifold

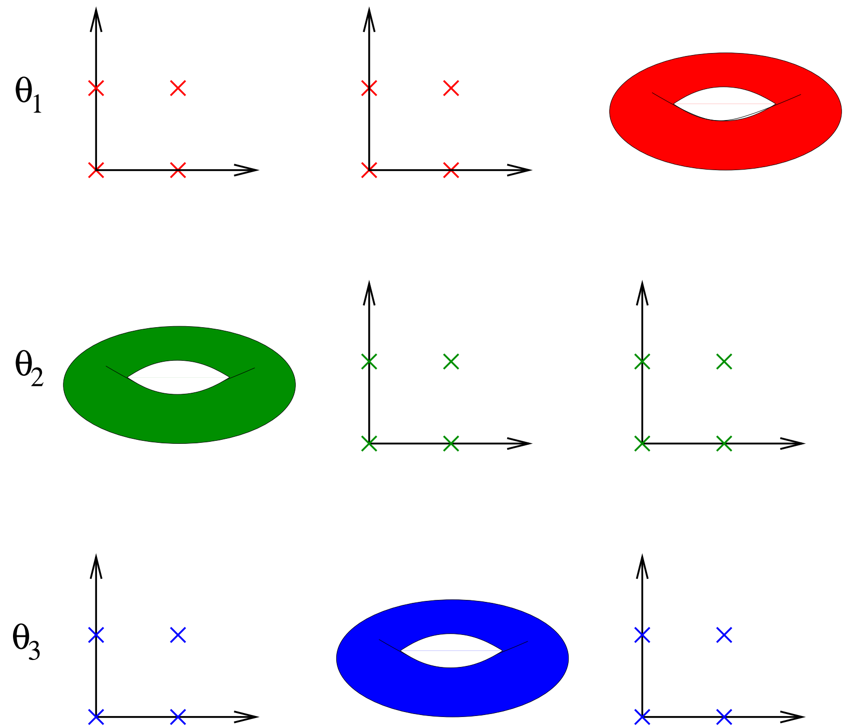
The Z_3 orbifold had fixed points but no fixed tori, leading to difficulties to

- incorporate a correctly normalized $U(1)$-hypercharge
- accomodate satisfactory Yukawa couplings

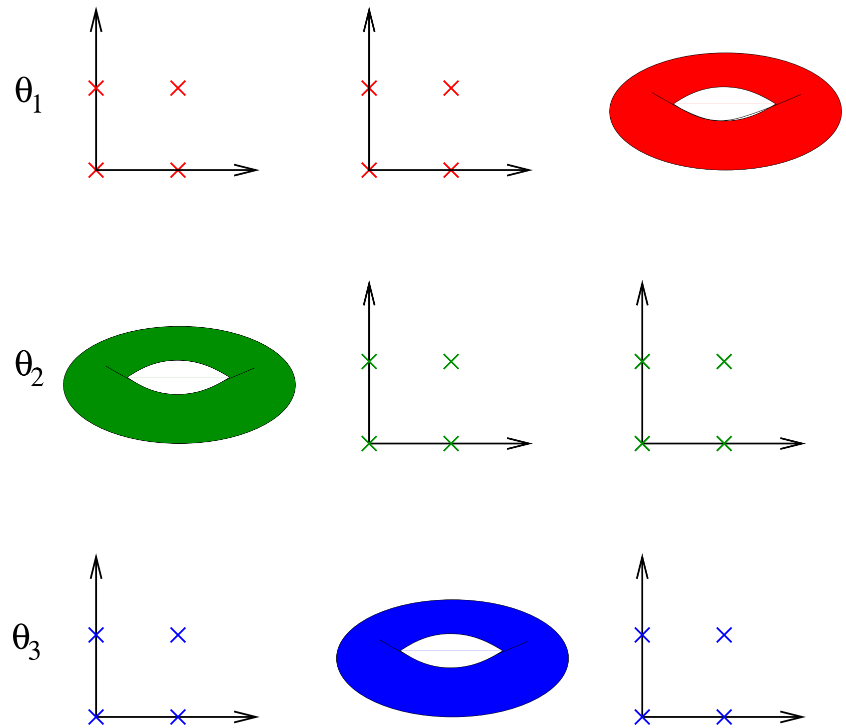
From this point of view, the Z_{2N} or $Z_N \times Z_M$ orbifolds do look more promising

(Foerste, HPN, Vaudrevange, Wingerter, 2004)

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

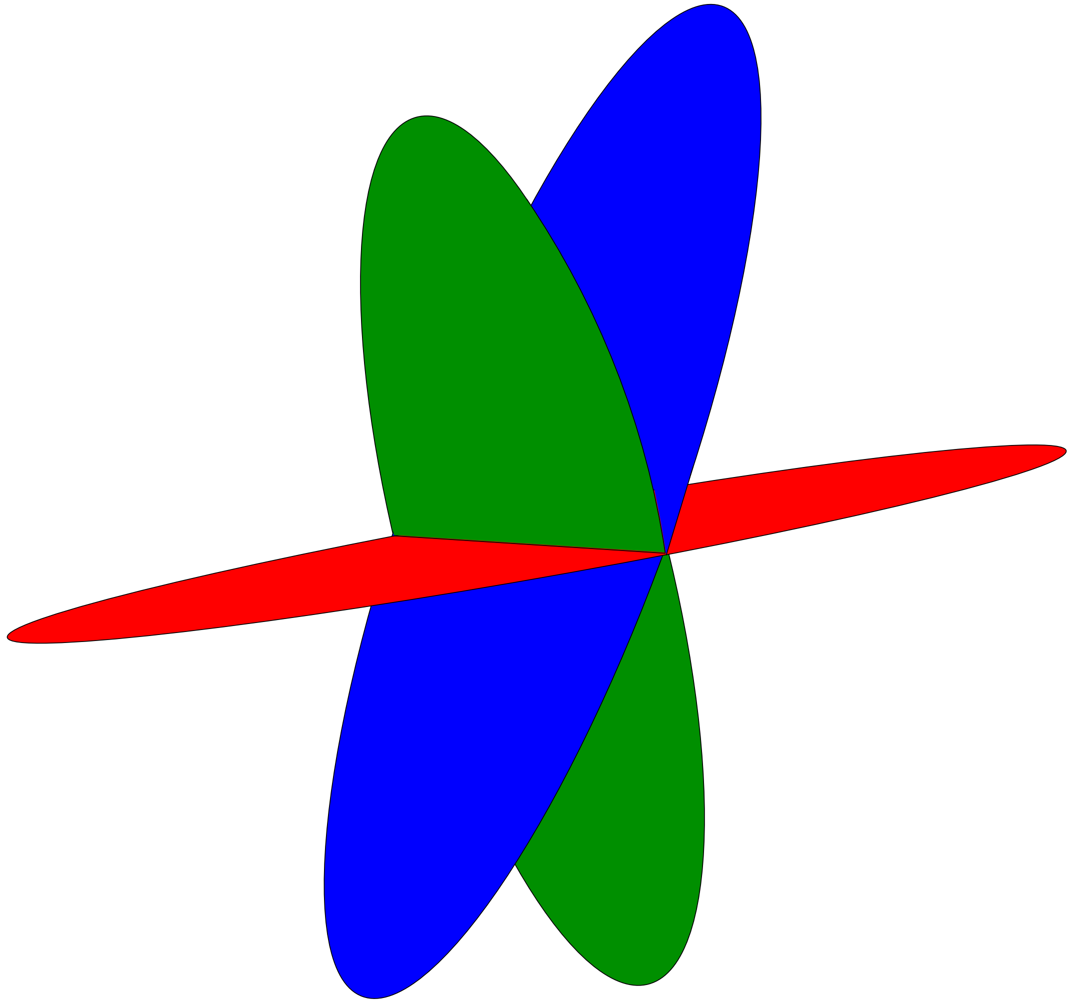


$\mathbb{Z}_2 \times \mathbb{Z}_2$ Orbifold Example



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

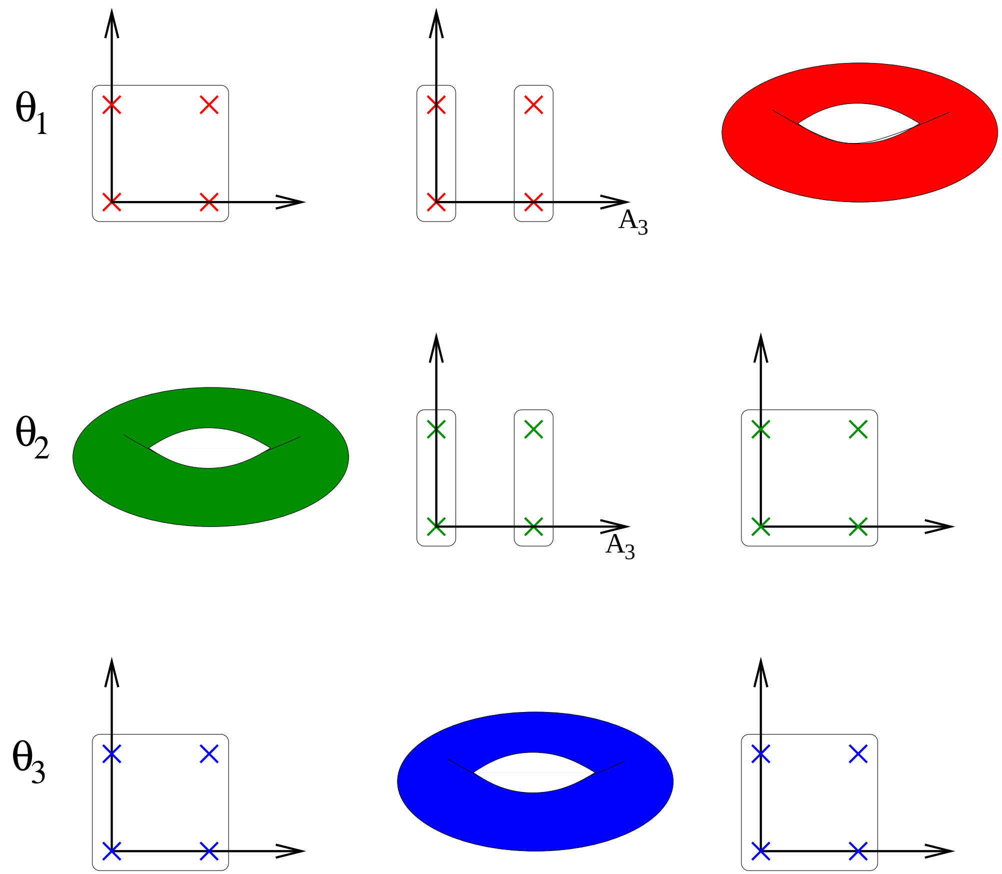
Intersecting Branes



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

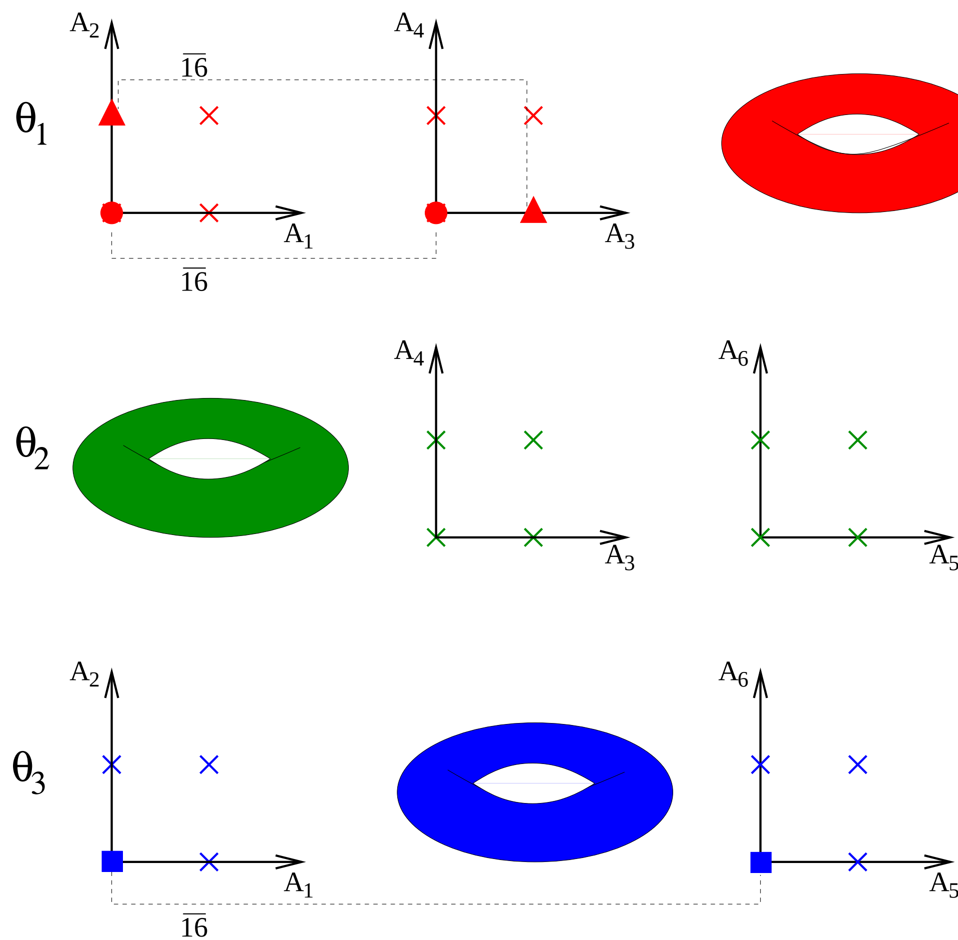
Case	Shifts	Gauge Group	Gen.
1	$\left(\frac{1}{2}, -\frac{1}{2}, 0^6\right)\ (0^8)$ $\left(0, \frac{1}{2}, -\frac{1}{2}, 0^5\right)\ (0^8)$	$\mathsf{E}_6 \times \mathsf{U}(1)^2 \times \mathsf{E}_8'$	48
2	$\left(\frac{1}{2}, -\frac{1}{2}, 0^6\right)\ (0^8)$ $\left(0, \frac{1}{2}, -\frac{1}{2}, 0^4, 1\right)\ (1, 0^7)$	$\mathsf{E}_6 \times \mathsf{U}(1)^2 \times \mathsf{SO}(16)'$	16
3	$\left({\frac{1}{2}}^2, 0^6\right)\ (0^8)$ $\left(\frac{5}{4}, {\frac{1}{4}}^7\right)\ \left(\frac{1}{2}, \frac{1}{2}, 0^6\right)$	$\mathsf{SU}(8) \times \mathsf{U}(1) \times \mathsf{E}_7' \times \mathsf{SU}(2)'$	16
4	$\left({\frac{1}{2}}^2, 0^5, 1\right)\ (1, 0^7)$ $\left(0, \frac{1}{2}, -\frac{1}{2}, 0^5\right)\ \left(-\frac{1}{2}, {\frac{1}{2}}^3, 1, 0^3\right)$	$\mathsf{E}_6 \times \mathsf{U}(1)^2 \times \mathsf{SO}(8)'^2$	0
5	$\left(\frac{1}{2}, -\frac{1}{2}, -1, 0^5\right)\ (1, 0^7)$ $\left(\frac{5}{4}, {\frac{1}{4}}^7\right)\ \left(\frac{1}{2}, \frac{1}{2}, 0^6\right)$	$\mathsf{SU}(8) \times \mathsf{U}(1) \times \mathsf{SO}(12)' \times \mathsf{SU}(2)'^2$	0

$\mathbb{Z}_2 \times \mathbb{Z}_2$ **with Wilson lines**



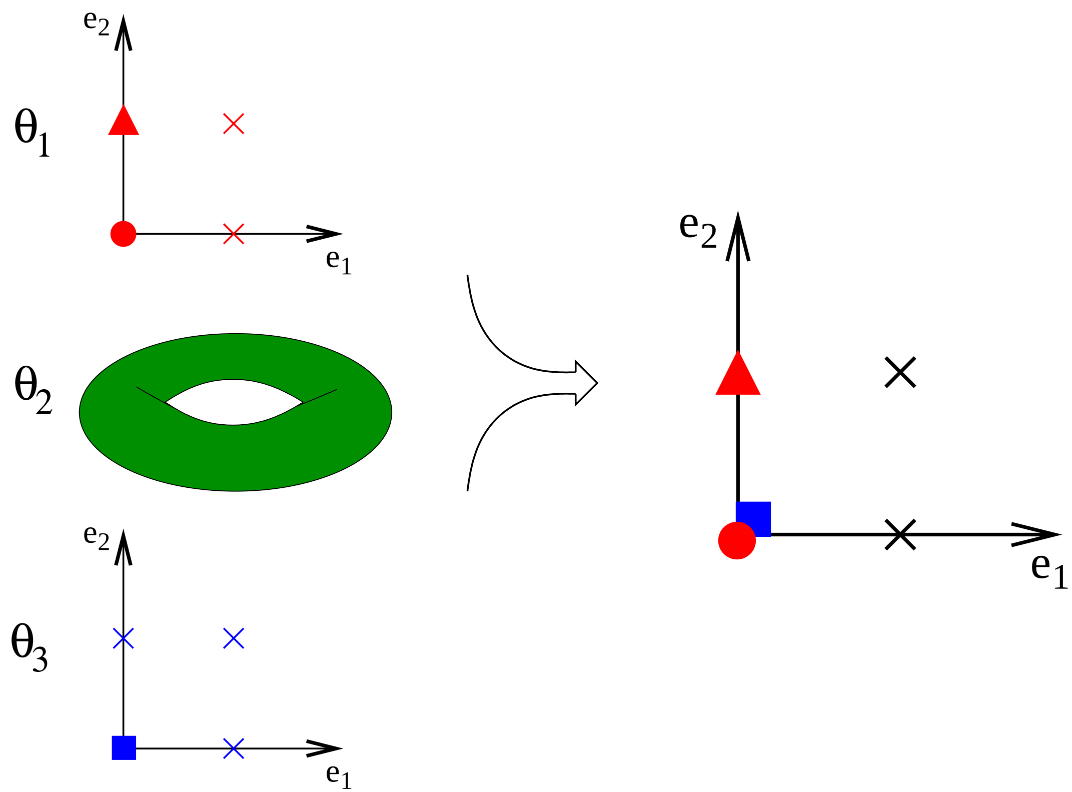
Again, Wilson lines can lift the degeneracy....

Three family $SO(10)$ toy model



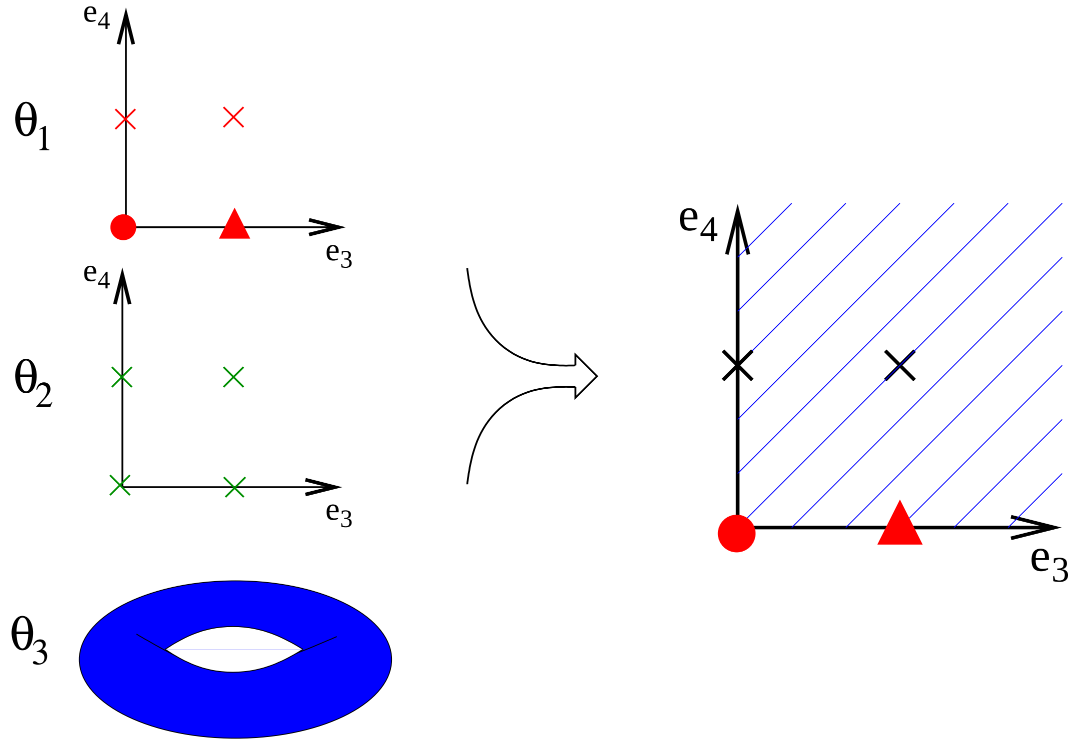
Localization of families at various fixed tori

Zoom on first torus ...



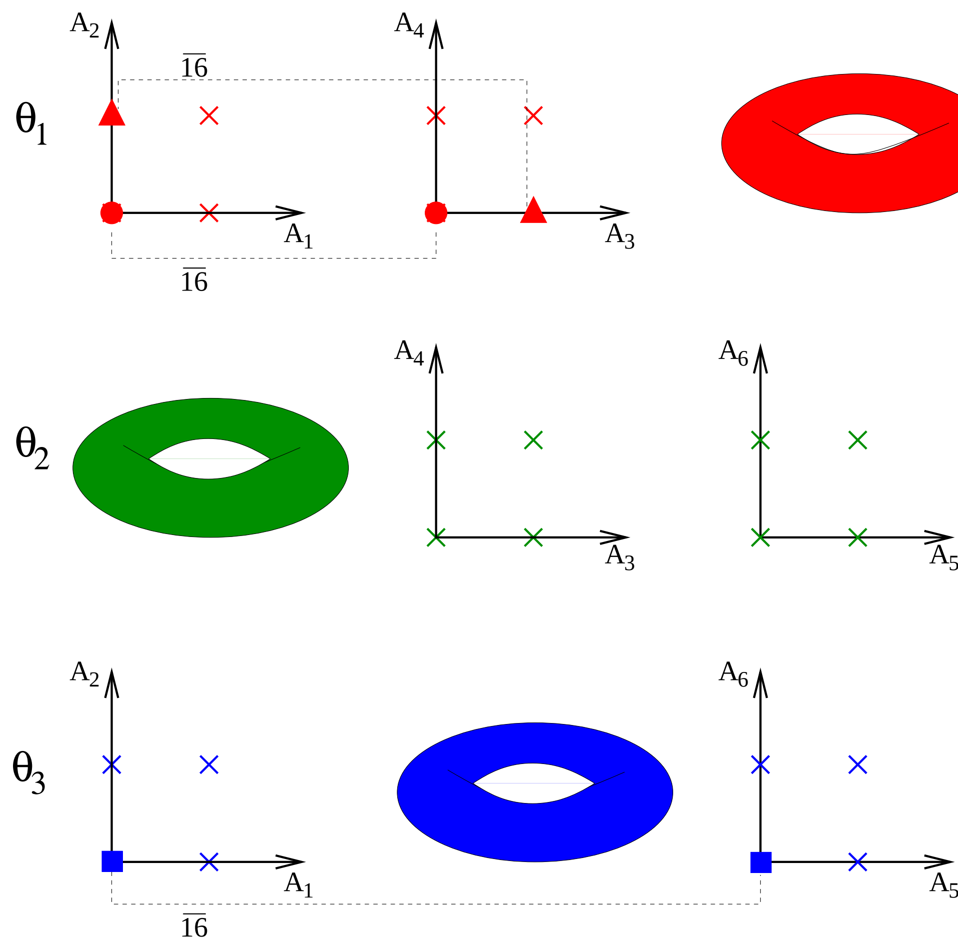
Interpretation as 6-dim. model with 3 families on branes

second torus ...



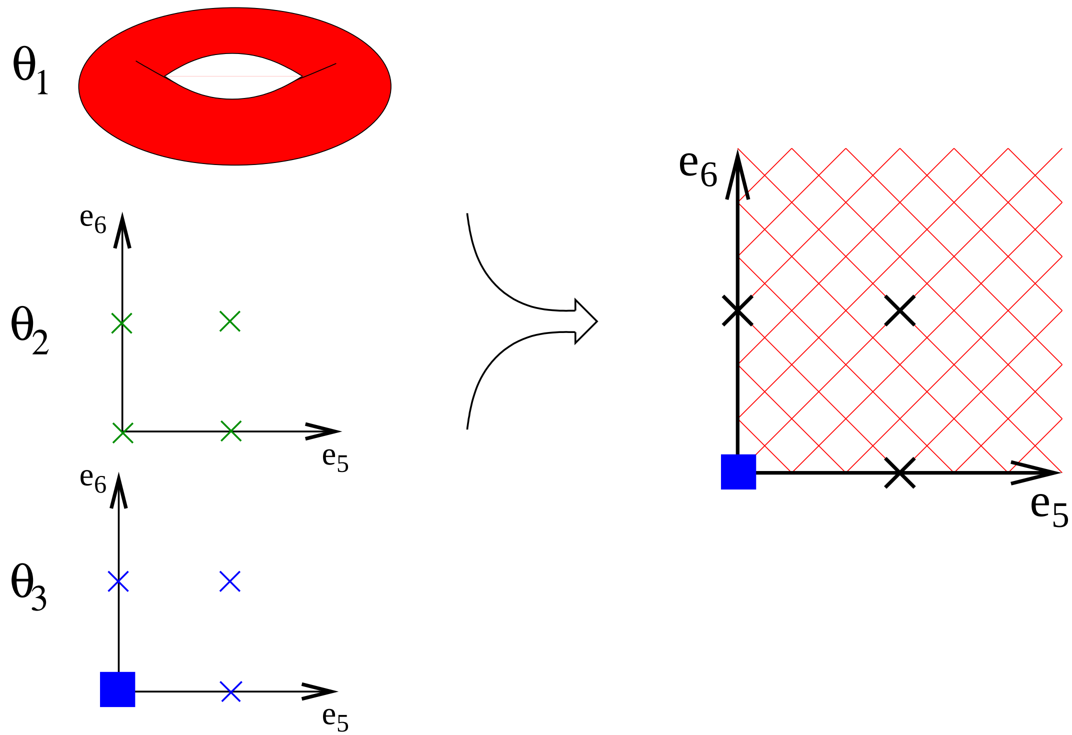
... 2 families on branes, one in (6d) bulk ...

Three family $SO(10)$ toy model



Localization of families at various fixed tori

third torus



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

Geography

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

Geography

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

- the location of quarks and leptons,

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,

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,
- the localized gauge symmetry at fixed points (tori).

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,
- the localized gauge symmetry at fixed points (tori).
- Discrete symmetries like family symmetries and R-parity might find their explanation in these geometric properties.
- Some small numbers (like suppressed Yukawa couplings) arise if fields are separated by a large distance

Model building

We can easily find

- models with gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- doublet-triplet splitting
- $N = 1$ supersymmetry

(Förste, HPN, Vaudrevange, Wingerter, 2004)

(Kobyashi, Raby, Zhang, 2004)

(Buchmüller, Hamaguchi, Lebedev, Ratz, 2004, 2005)

Model building

We can easily find

- models with gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- doublet-triplet splitting
- $N = 1$ supersymmetry (Förste, HPN, Vaudrevange, Wingerter, 2004)

(Kobyashi, Raby, Zhang, 2004)

(Buchmüller, Hamaguchi, Lebedev, Ratz, 2004, 2005)

But explicit model building is tedious:

- removal of exotic states
- R parity
- “correct” hypercharge

Model building (II)

We do not yet have a complete understanding of the origin of these specific problems.

Model building (II)

We do not yet have a complete understanding of the origin of these specific problems.

Key properties of the models depend on geometry:

- family symmetries
- texture of Yukawa couplings
- number of families
- local gauge groups on branes
- electroweak symmetry breakdown

Model building (II)

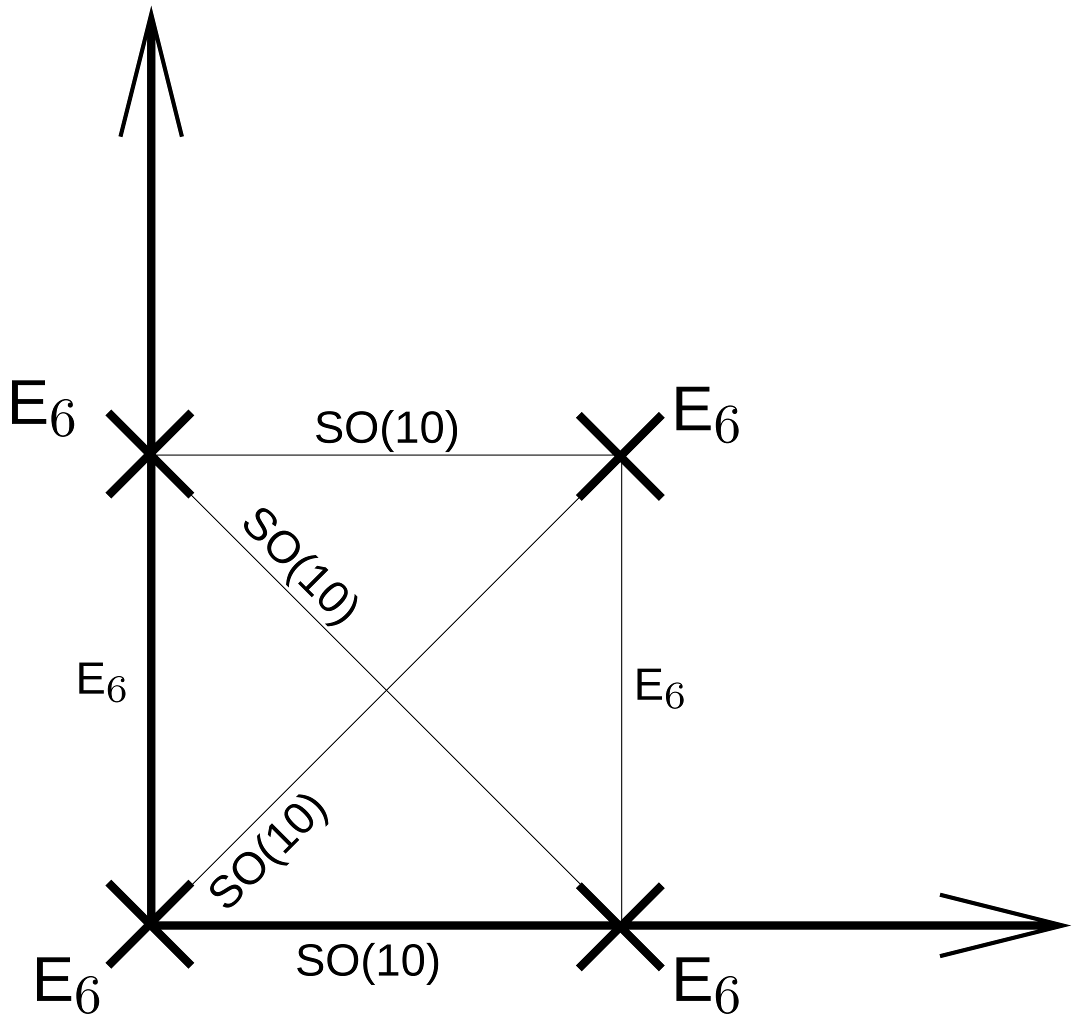
We do not yet have a complete understanding of the origin of these specific problems.

Key properties of the models depend on geometry:

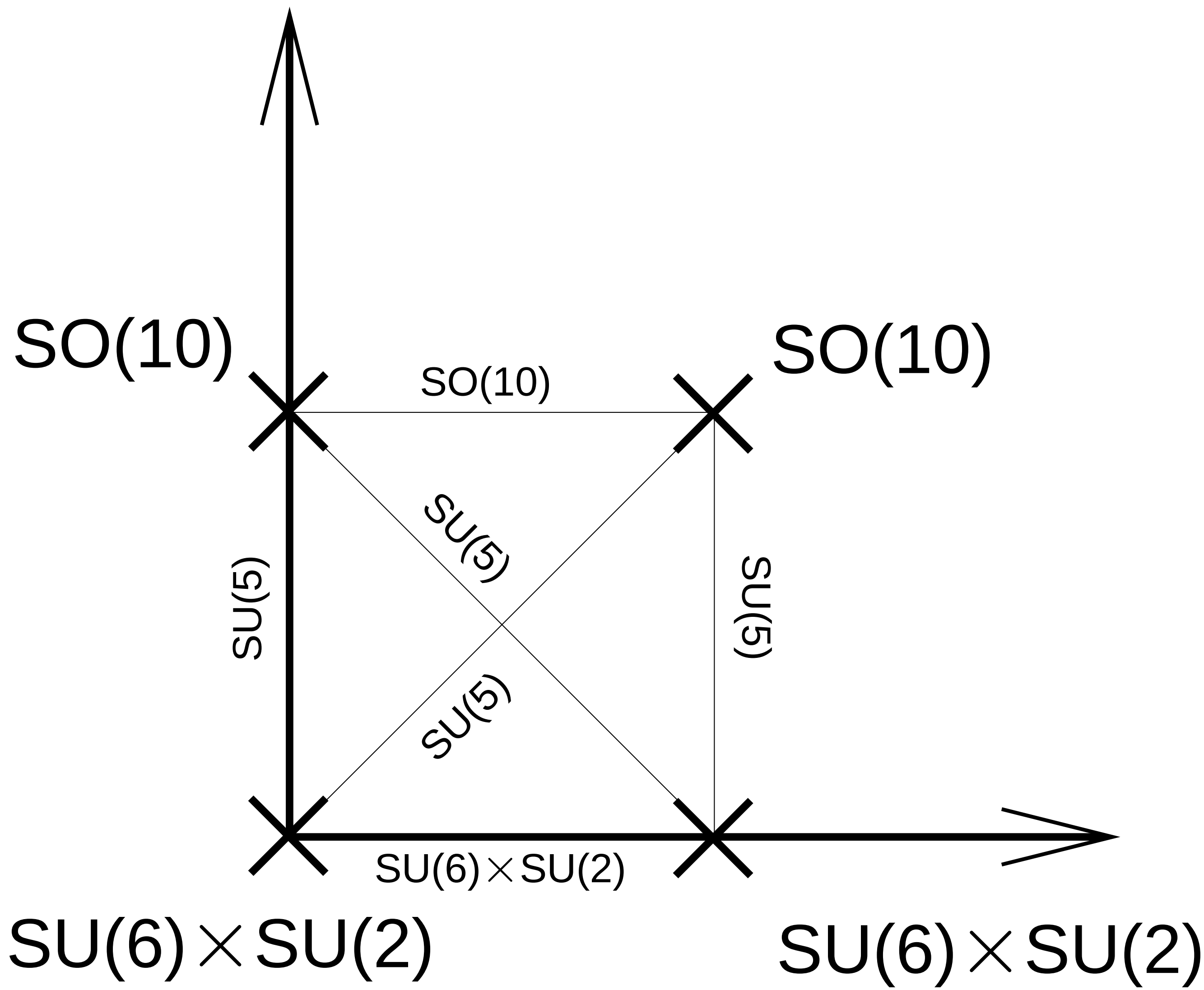
- family symmetries
- texture of Yukawa couplings
- number of families
- local gauge groups on branes
- electroweak symmetry breakdown

We need to exploit these geometric properties......

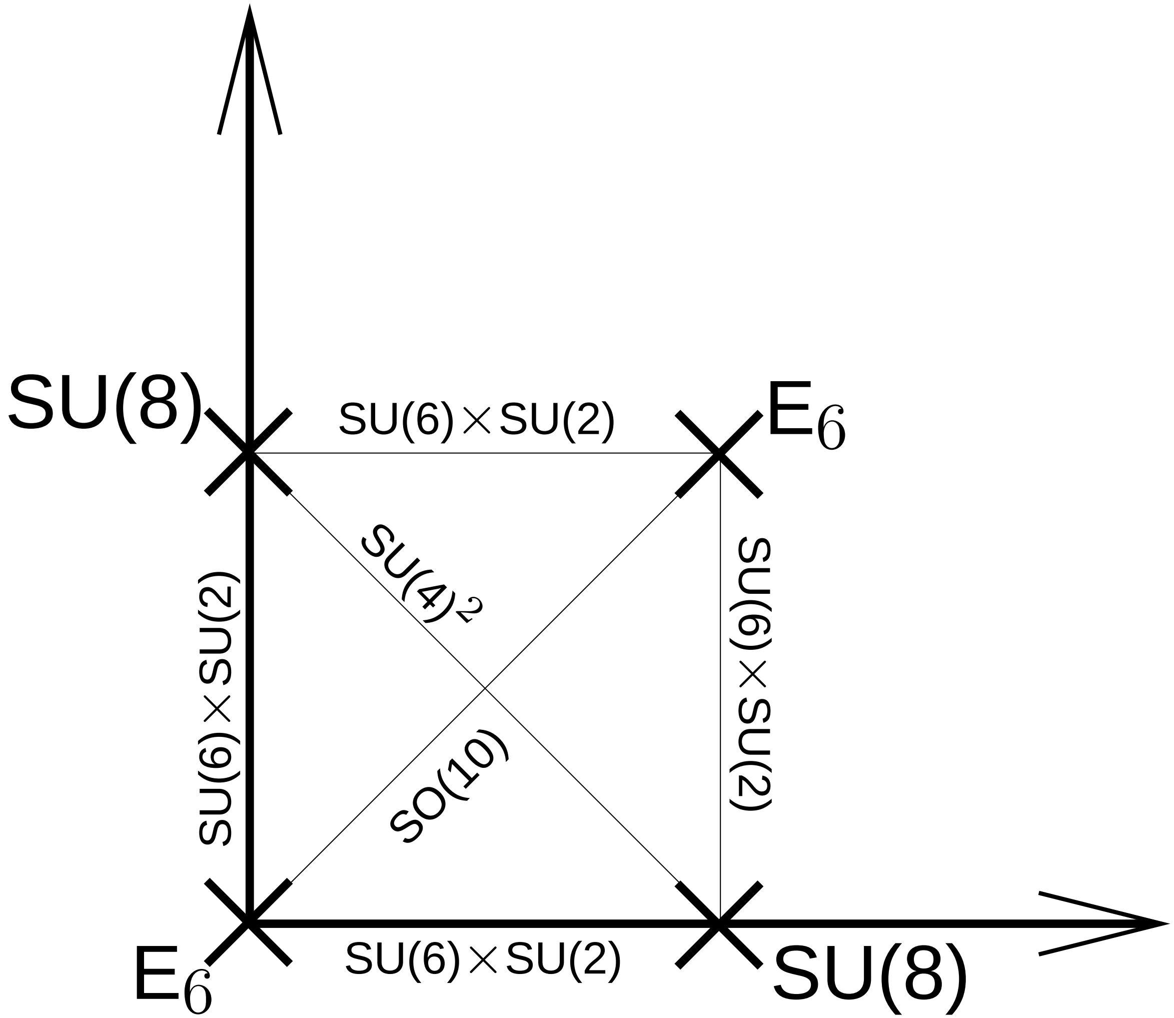
Gauge group geography SO(10)



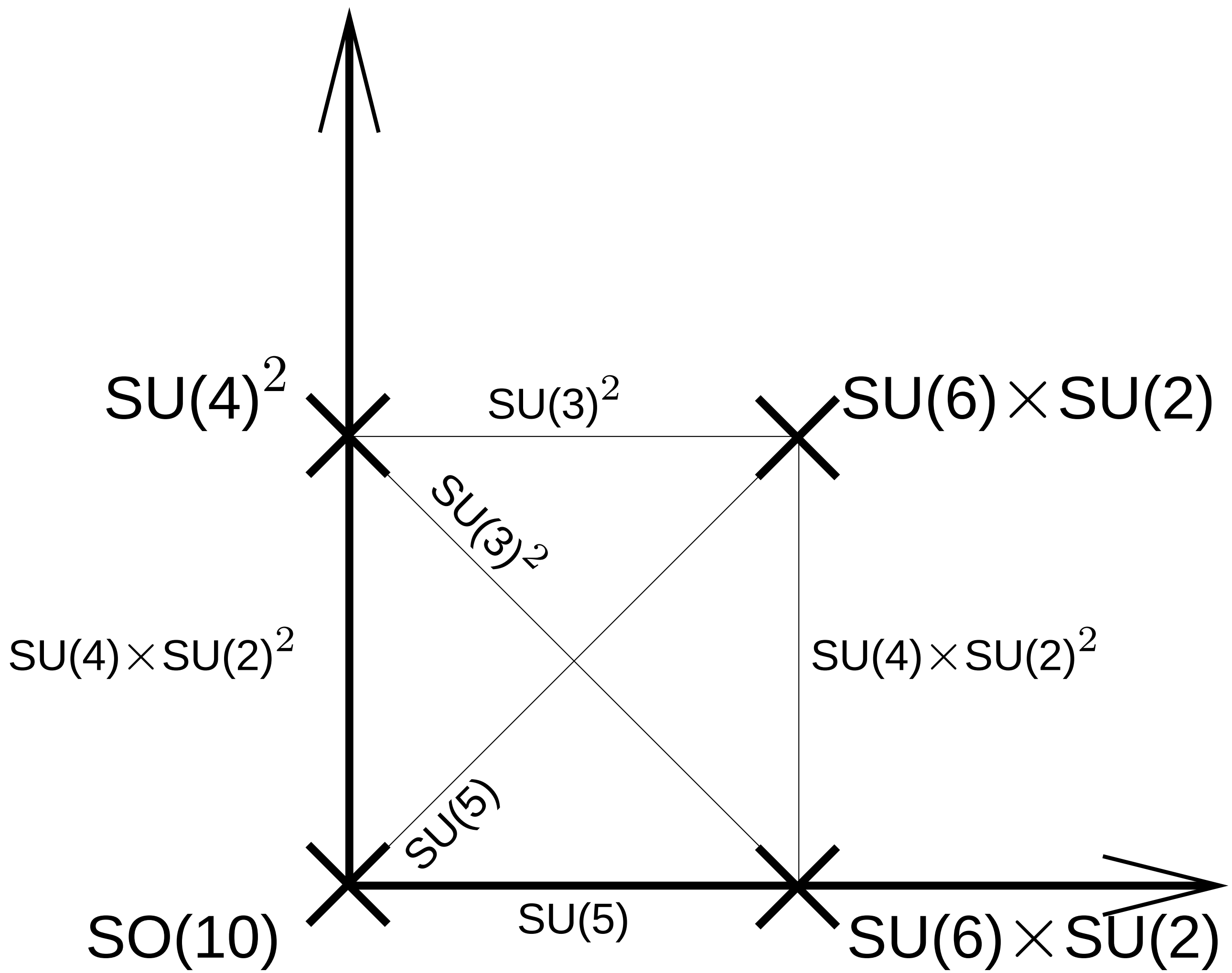
Gauge group geography SU(5)



Gauge group geography: Pati-Salam



Gauge geography: Standard Model



The Memory of SO(10)

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

The Memory of SO(10)

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

There could still be remnants of $SO(10)$ symmetry

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

that are very useful for realistic model building ...

Proton decay

- R-parity from SO(10) memory avoids dangerous dimension-4 operators

Proton decay

- R-parity from SO(10) memory avoids dangerous dimension-4 operators
- No proton decay via dimension-5 operators because of doublet-triplet splitting

Proton decay

- R-parity from SO(10) memory avoids dangerous dimension-4 operators
- No proton decay via dimension-5 operators because of doublet-triplet splitting
- Avoid SO(10) brane for first family: suppressed p-decay via dimension-6 operators

Proton decay

- R-parity from SO(10) memory avoids dangerous dimension-4 operators
- No proton decay via dimension-5 operators because of doublet-triplet splitting
- Avoid SO(10) brane for first family:
  suppressed p-decay via dimension-6 operators

Thus the proton could be practically stable!

Unification

- SO(10) memory provides a reasonable value of $\sin^2\theta_W$ and a unified definition of hypercharge

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 sizable threshold corrections at the high scale to match string and unification scale

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 sizable threshold corrections at the high scale to match string and unification scale
- Yukawa unification from SO(10) memory for third family (on an SO(10) brane)

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 sizable threshold corrections at the high scale to match string and unification scale

- Yukawa unification from SO(10) memory for third family (on an SO(10) brane)

- no Yukawa unification for first and second family required

Yukawa textures and family symmetries

- Yukawa couplings depend on location of Higgs and matter fields

Yukawa textures and family symmetries

- Yukawa couplings depend on location of Higgs and matter fields
- family symmetries arise if different fields live on the same brane

Yukawa textures and family symmetries

- Yukawa couplings depend on location of Higgs and matter fields
- family symmetries arise if different fields live on the same brane
- Exponential suppression if fields at distant branes

Yukawa textures and family symmetries

- Yukawa couplings depend on location of Higgs and matter fields
- family symmetries arise if different fields live on the same brane
- Exponential suppression if fields at distant branes
- neutrino Majorana masses might need some bulk mixing (presence of anti-families)

Yukawa textures and family symmetries

- Yukawa couplings depend on location of Higgs and matter fields
- family symmetries arise if different fields live on the same brane
- Exponential suppression if fields at distant branes
- neutrino Majorana masses might need some bulk mixing (presence of anti-families)
- GUT relations could be partially present, depending on the nature of the brane (e.g. SO(10) brane)

It's a long way to go

Full classification seems to be too difficult (at the moment).
Work in progress:

It's a long way to go

Full classification seems to be too difficult (at the moment). Work in progress:

- $SO(32)$ classification (with $SO(10)$ spinors)

  (Choi, Groot Nibbelink, Trapletti, 2004)

  (Ramos-Sanchez, Vaudrevange, Wingerter, 2006)

It's a long way to go

Full classification seems to be too difficult (at the moment). Work in progress:

- $SO(32)$ classification (with $SO(10)$ spinors)

  (Choi, Groot Nibbelink, Trapletti, 2004)

  (Ramos-Sanchez, Vaudrevange, Wingerter, 2006)

- (partial) classification of $Z_2 \times Z_2$ and $Z_2 \times Z_3$

  (HPN, Ploeger, Ramos-Sanchez, Ratz, Vaudrevange, 2006)

It's a long way to go

Full classification seems to be too difficult (at the moment). Work in progress:

- $SO(32)$ classification (with $SO(10)$ spinors)

  (Choi, Groot Nibbelink, Trapletti, 2004)

  (Ramos-Sanchez, Vaudrevange, Wingerter, 2006)

- (partial) classification of $Z_2 \times Z_2$ and $Z_2 \times Z_3$

  (HPN, Ploeger, Ramos-Sanchez, Ratz, Vaudrevange, 2006)

- smooth breakdown of gauge group

  (Förste, HPN, Wingerter, 2005)

Specific models

- $Z_2 \times Z_3$ Pati-Salam model

(Kobyashi, Raby, Zhang, 2004)

Specific models

- $Z_2 \times Z_3$ Pati-Salam model

  (Kobyashi, Raby, Zhang, 2004)

- $Z_2 \times Z_3$ standard model

  (Buchmüller, Hamaguchi, Lebedev, Ratz, 2005)

Specific models

- $Z_2 \times Z_3$ Pati-Salam model

  (Kobyashi, Raby, Zhang, 2004)

- $Z_2 \times Z_3$ standard model

  (Buchmüller, Hamaguchi, Lebedev, Ratz, 2005)

- standard model in fermionic formulation

  (Faraggi et al., 92)

Specific models

- $Z_2 \times Z_3$ Pati-Salam model

  (Kobyashi, Raby, Zhang, 2004)

- $Z_2 \times Z_3$ standard model

  (Buchmüller, Hamaguchi, Lebedev, Ratz, 2005)

- standard model in fermionic formulation

  (Faraggi et al., 92)

- standard model on specific Calabi-Yau orbifold

  (Ovrut et al., 2005)

The Higgs-mechanism in string theory...

...can be achieved via continuous Wilson lines. The aim is:

The Higgs-mechanism in string theory...

...can be achieved via continuous Wilson lines. The aim is:

- electroweak symmetry breakdown
- breakdown of Trinification or Pati-Salam group to the Standard Model gauge group
- rank reduction

The Higgs-mechanism in string theory...

...can be achieved via continuous Wilson lines. The aim is:

- electroweak symmetry breakdown
- breakdown of Trinification or Pati-Salam group to the Standard Model gauge group
- rank reduction

Continuous Wilson lines require specific embeddings of twist in the gauge group

(Ibanez, HPN, Quevedo, 1987)

- difficult to implement in the Z_3 case
- more promising for Z_2 twists

An example

We consider a model that has E_6 gauge group in the bulk of a "6d orbifold". The breakdown pattern is

An example

We consider a model that has E_6 gauge group in the bulk of a “6d orbifold”. The breakdown pattern is

- $E_6 \to SO(10)$ via a Z_2 twist
- $SO(10) \to SU(4) \times SU(2) \times SU(2) \times U(1)$ via a discrete (quantized) Wilson line
- $SU(4) \times SU(2) \times SU(2) \to SU(3) \times SU(2) \times U(1)$ via a continuous Wilson line (Förste, HPN, Wingerter, 2005)

An example

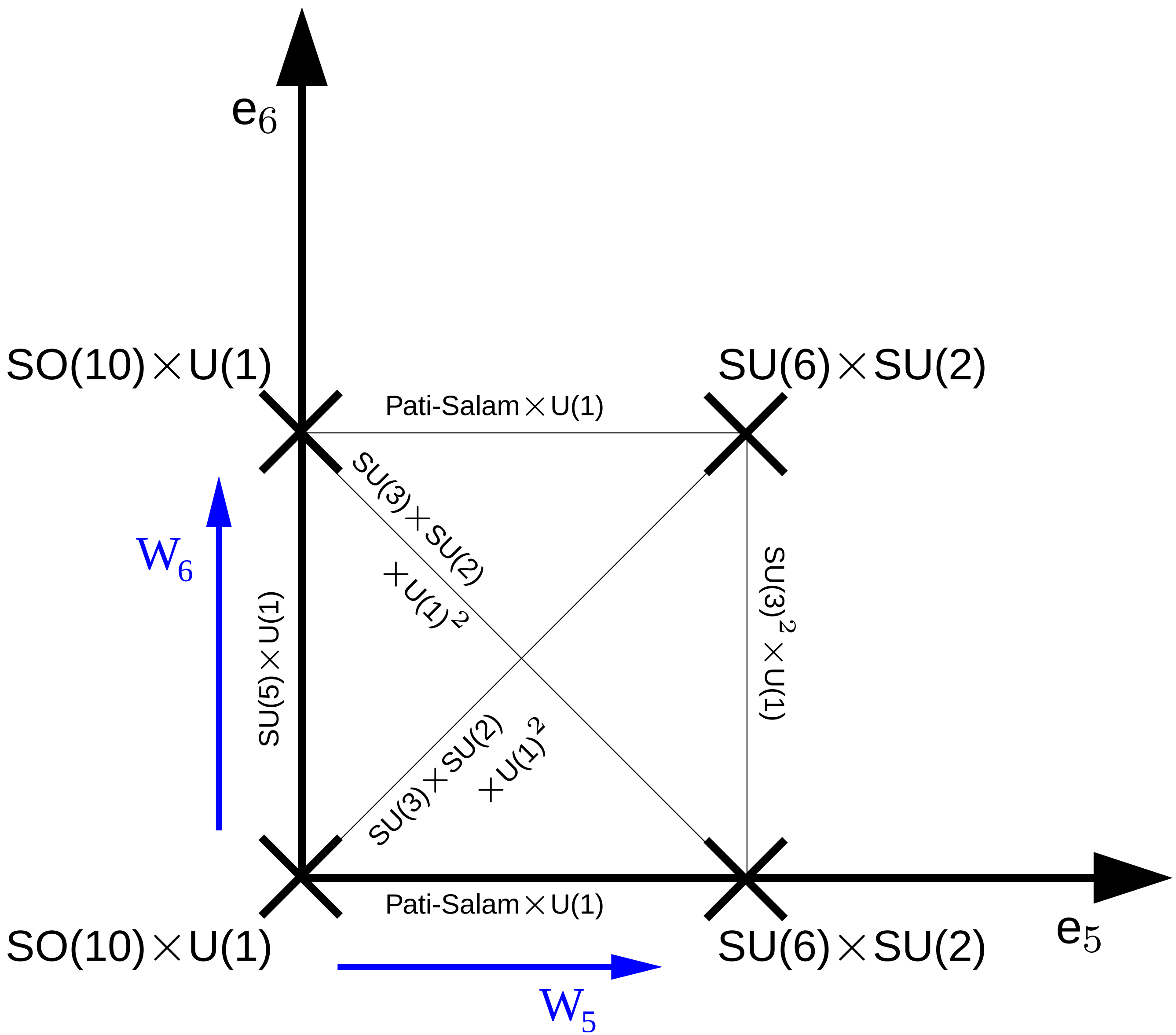
We consider a model that has E_6 gauge group in the bulk of a "6d orbifold". The breakdown pattern is

- $E_6 \rightarrow SO(10)$ via a Z_2 twist
- $SO(10) \rightarrow SU(4) \times SU(2) \times SU(2) \times U(1)$ via a discrete (quantized) Wilson line
- $SU(4) \times SU(2) \times SU(2) \rightarrow SU(3) \times SU(2) \times U(1)$ via a continuous Wilson line (Förste, HPN, Wingerter, 2005)

Such 6d models can be embedded in 10d string theory orbifolds. Models with consistent electroweak symmetry breakdown have been constructed.

(Förste, HPN, Wingerter, 2006)

Pati-Salam breakdown



Conclusion

Heterotic string compactifications might lead to models that incorporate all the successful ingredients of grand unified theories, while avoiding the problematic ones.

- spinor representations of SO(10)
- geometric origin of (three) families
- incomplete multiplets
- supersymmetric unification
- R-parity
- “absence” of proton decay
- gauge-Yukawa unification (partial GUT relations)
- discrete family symmetries