CP-Violation from Strings

Hans Peter Nilles

Physikalisches Institut

Universität Bonn

universitätbonn

bctp

Bethe Center for
Theoretical Physics

Role of CP and its violation

CP (violation) is relevant for several phenomena:

- CP violation in standard model (CKM phase)
- the strong CP-problem ($\Theta_{\rm QCD}$)
- matter-antimatter asymmetry of the universe

While P and C are maximally violated in weak interactions, CP seems only to be "slightly" broken

- Origin of CP symmetry? How is it broken?
- Is it related to flavour symmetries?

CP: make it and break it. Is there a top-down explanation?

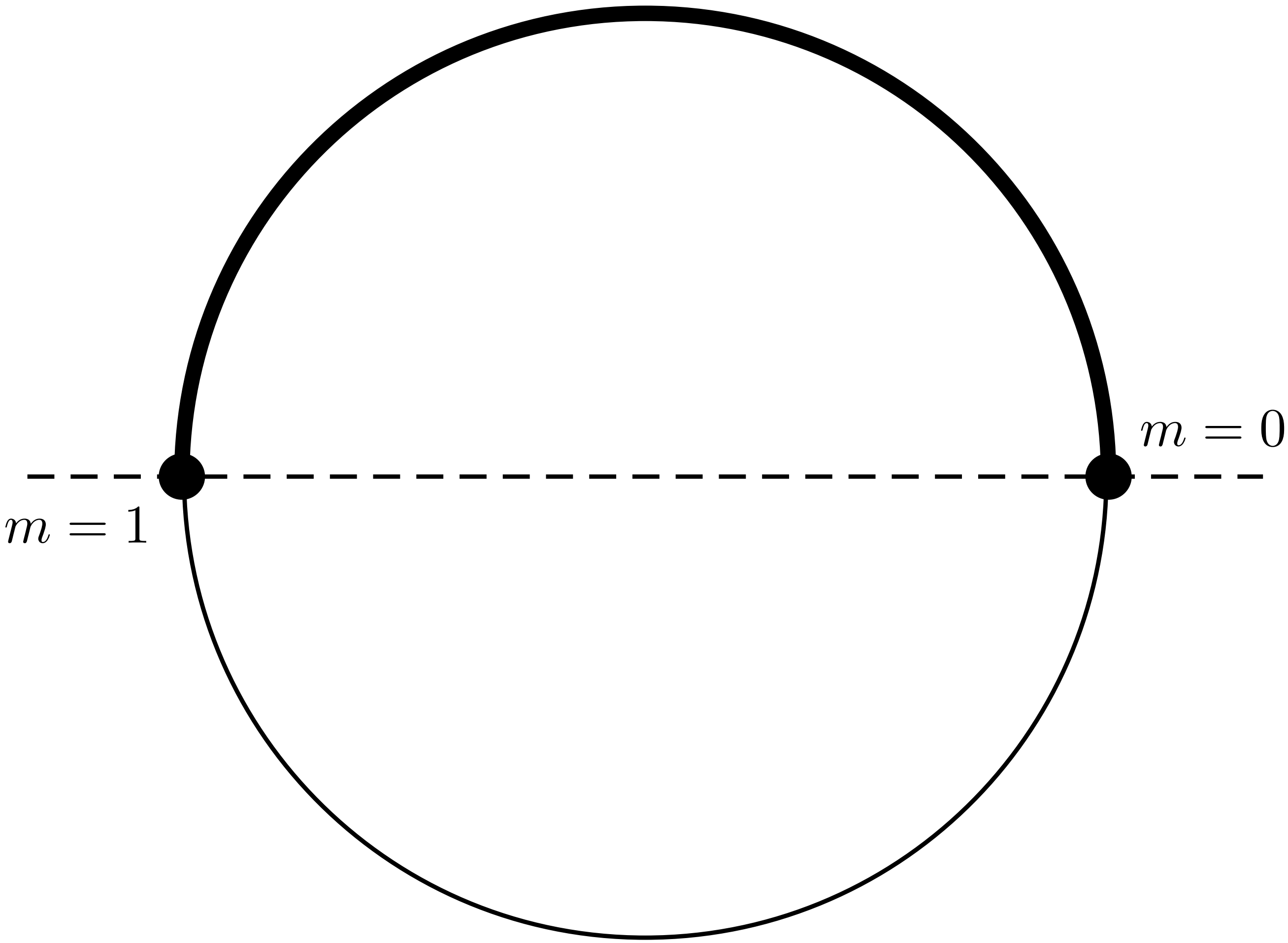
Outline

CP as a discrete symmetry from string theory. A low energy symmetry broken in the presence of heavy string modes.

- discrete symmetries in string theory
- flavour groups and CP as outer automorphism
- the concept of "explicit geometric CP-violation"
- model examples from the heterotic Mini-Landscape
- CP symmetry in low-energy effective theory
- the role of massive winding modes
- Lepto-genesis from decay of heavy particles
- intrinsic sources for Θ angle and Jarlskog determinant

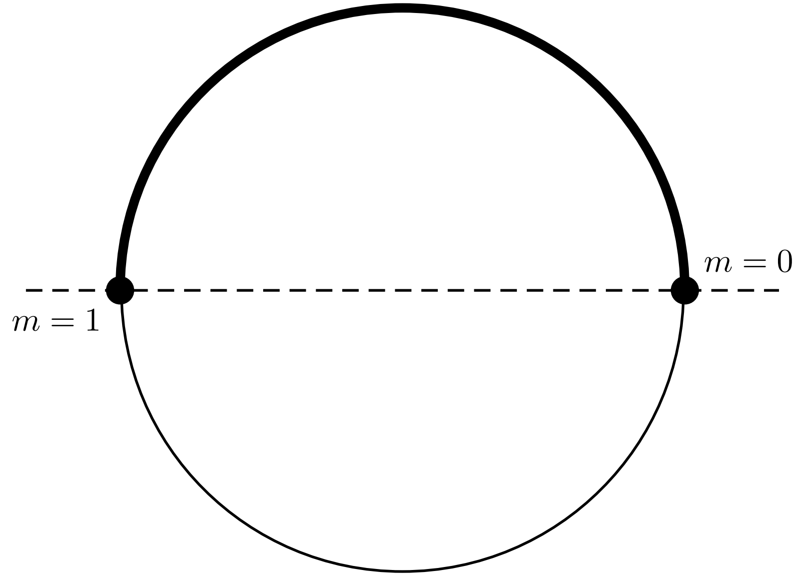
(Nilles, Ratz, Trautner, Vaudrevange, to appear)

Interval S_1/Z_2



Discrete symmetry D_4

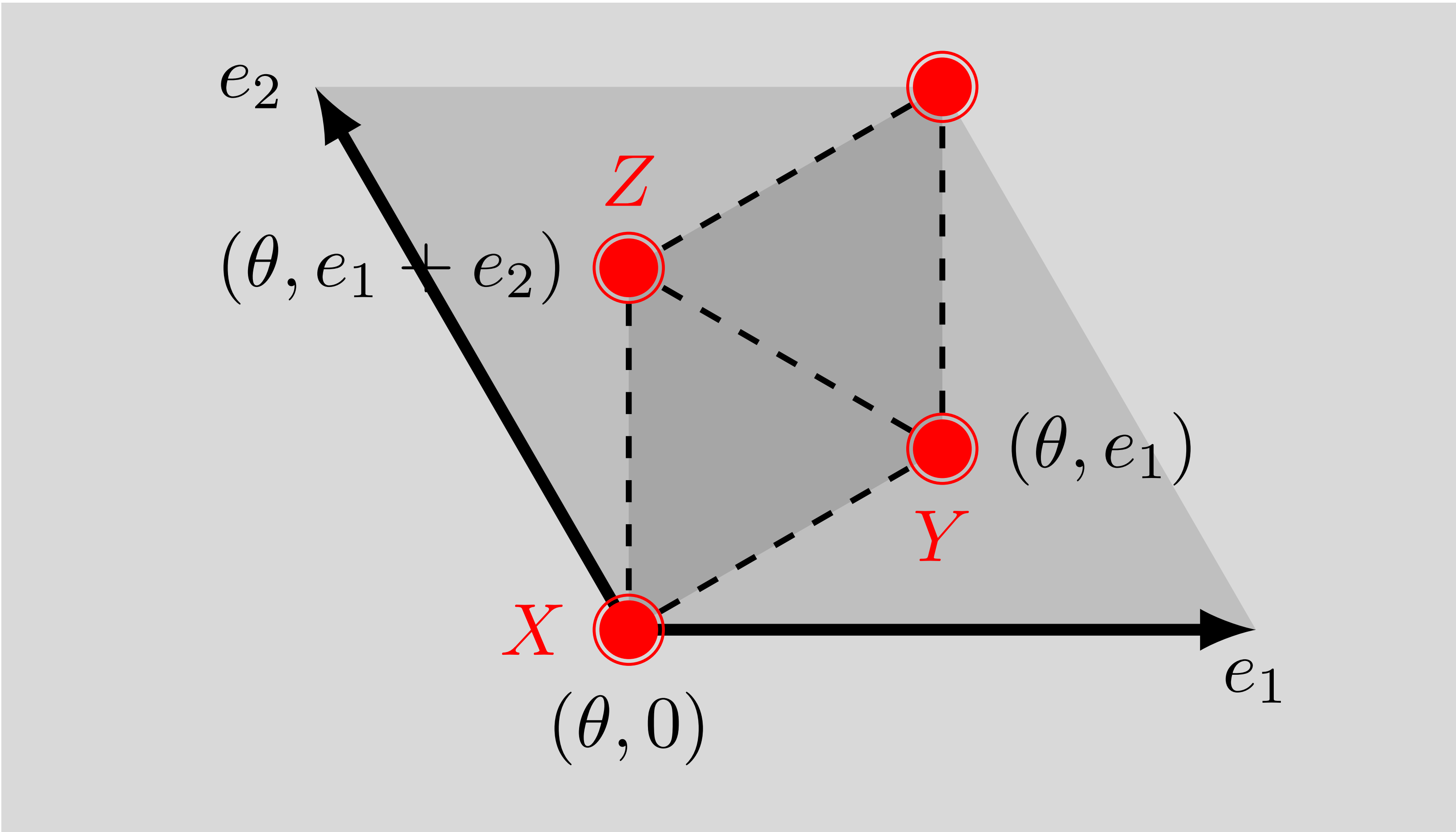
- bulk and brane fields
- S_2 symmetry from interchange of fixed points
- $Z_2 \times Z_2$ symmetry from brane field selection rules



- D_4 as multiplicative closure of S_2 and $Z_2 \times Z_2$
- D_4 – a nonabelian subgroup of $SU(2)_{\text{flavor}}$
- flavor symmetry for the two lightest families

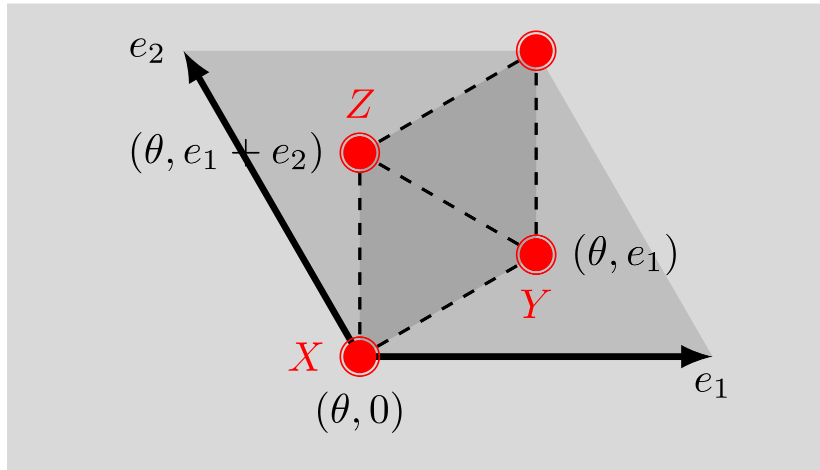
(Kobayashi, Nilles, Ploeger, Raby, Ratz, 2006)

Orbifold T_2/Z_3



Discrete symmetry $\Delta(54)$

- untwisted and twisted fields
- S_3 symmetry from interchange of fixed points
- $Z_3 \times Z_3$ symmetry from orbifold selection rules



- $\Delta(54)$ as multiplicative closure of S_3 and $Z_3 \times Z_3$
- $\Delta(54)$ – a nonabelian subgroup of $SU(3)_{\text{flavor}}$
- flavor symmetry for three families of quarks and leptons

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

$\Delta(54)$ group theory

$\Delta(54)$ is a nonabelian group and has representations:

- one trivial singlet 1_0 and one nontrivial singlet 1_-
- two triplets 3_1, 3_2 and corresponding anti-triplets $\bar{3}_1$, $\bar{3}_2$
- four doublets 2_k ($k = 1, 2, 3, 4$)

Some relevant tensor products are:

- $3_1 \otimes \bar{3}_1 = 1_0 \oplus 2_1 \oplus 2_2 \oplus 2_3 \oplus 2_4$
- $2_k \otimes 2_k = 1_0 \oplus 1_- \oplus 2_k$

$\Delta(54)$ is a good candidate for a flavour symmetry.

But where is CP?

CP as outer automorphism

Outer automorphisms map group to itself but are not group elements themselves

- $\Delta(54)$ has outer automorphism group S_4
- CP could be Z_2 subgroup of this S_4
- Physical CP transforms (rep) to $(rep)^*$

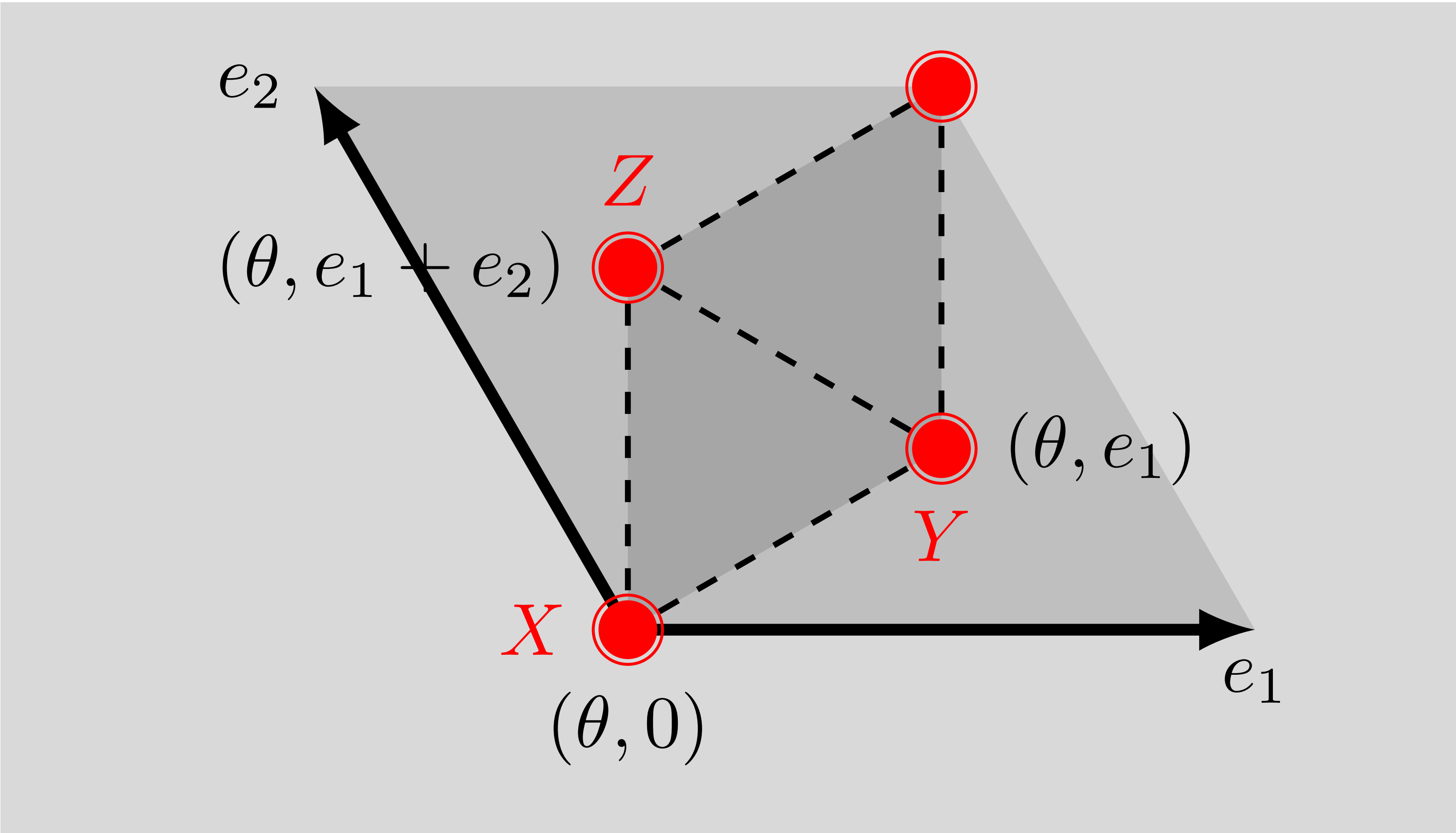
This gives an intimate relation of flavour and CP symmetry

- possible obstructions for a successful definition of CP
- controlled by "twisted Frobenius-Schur indicator"
- could lead to "explicit geometric CP violation"

(Holthausen, Lindner, Schmidt, 2012;

Chen, Fallbacher, Mahanthappa, Ratz, Trautner, 2014)

Orbifold T_2/Z_3



T_2/Z_3 orbifold examples

We label a string state by its constructing element $g = (\theta^k, n_\alpha e_\alpha)$ of the orbifold space group with

- $SU(3)$ lattice vectors e_1 and e_2
- twist θ (of 120 degrees) with $\theta^3 = 1$

This leads to different classes of closed string states

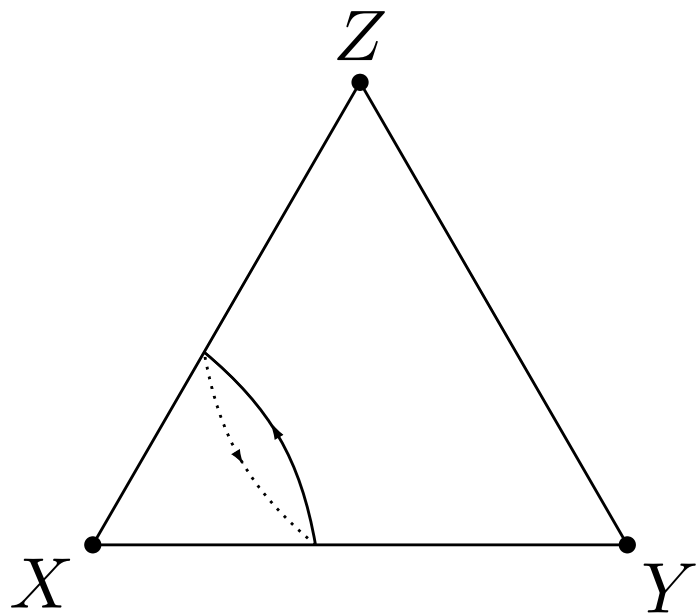
- untwisted states closed on the 2d plane
- winding states $(1, e_i)$ closed on the torus
- twisted states (θ, e_i) closed on the orbifold

How do they transform under $\Delta(54)$ and CP?

Twisted States

While untwisted states transform as singlets, the twisted states transform nontrivially

- twisted fields $(\theta, 0)$, (θ, e_1) and $(\theta, e_1 + e_2)$ transform as triplets under $\Delta(54)$
- states in the θ^2 sector are anti-triplets
- they wind around fixed points X, Y and Z



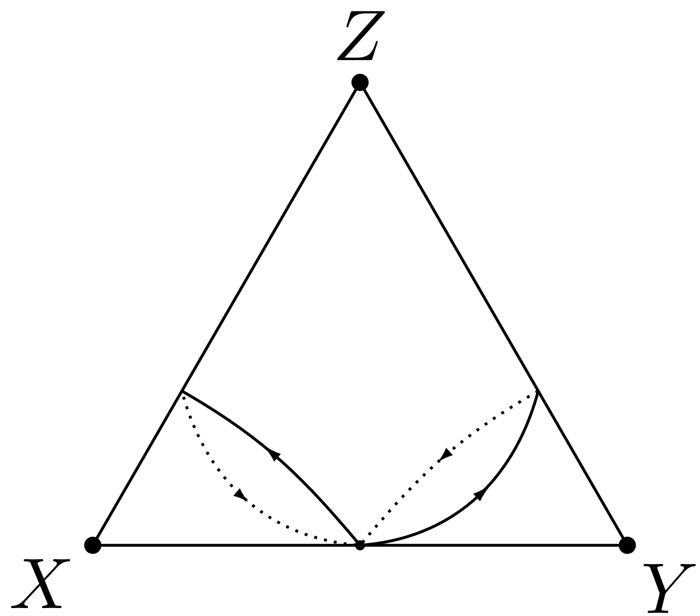
CP maps triplets (anti-triplets) to their complex conjugates

Winding States

Winding states are represented by the geometric elements:

$$V_1 = (1, e_1),\ V_2 = (1, e_2) \text{ and } V_3 = (1, -e_1 - e_2)$$

- the V_i wind around two fixed points with opposite orientation
- winding states $\overline{V}_i$ $i = 1, 2, 3$ have negative winding number



- the geometric winding states V_i and $\overline{V}_i$ do not transform covariantly under $\Delta(54)$

Doublets of $\Delta(54)$

We have to consider linear combinations $[n, \gamma]$

- $$[1, \gamma] = V_1 + \exp(-2\pi i\gamma)V_2 + \exp(-4\pi i\gamma)V_3$$

to obtain covariant states. This leads to doublets of $\Delta(54)$:

- $2_1 = (W_1, \overline{W}_1)$ with $W_1 = [-1, 0]$
- $2_3 = (W_2, \overline{W}_2)$ with $W_2 = \exp(4\pi i/3)[-1, -1/3]$
- $2_4 = (\overline{W}_3, W_3)$ with $W_3 = \exp(2\pi i/3)[-1, 1/3]$

States with positive and negative winding number form the two components of the individual doublets.

Generically, the windings modes are massive. Otherwise we would have symmetry enhancement (Narain lattice).

Examples from MiniLandscape

There are many examples in the heterotic MiniLandscape

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

- with T_2/Z_3 subsectors
- and potential $\Delta(54)$ symmetry

An inspection of the spectrum reveals that the massless modes transform as

- singlets (untwisted sector)
- triplets (anti-triplets) in θ- (θ^2-) twisted sectors
- there are no doublets in the massless spectrum!!!

For an example see: (Carballo-Perez, Peinado, Ramos-Sanchez, 2016)

CP-symmetry and its violation

We consider CP as a subgroup of S_4 of the outer automorphism of $\Delta(54)$

- CP transforms (rep) to $(rep)^*$
- this is possible for singlets and triplets
- possible simultaneously for up to two doublets
- impossible in the presence of three or more doublets

The low-energy effective theory allows CP symmetry

- which is broken in the presence of winding modes
- physical CP-violation arises if there are at least three doublets (here 2_1, 2_3 and 2_4) (Trautner, 2017)

CP-violation in physics

The relevance for physics includes

- CP-violation in the standard model (Jarlskog angle)
- the Θ-parameter of QCD
- CP violation for baryo/lepto-genesis

We have special form of of CP symmetry and CP-violation

- "Explicit geometric CP-violation"
- CP as outer automorphism of flavour symmetry
- CP symmetry for the low energy effective theory broken in the presence of (at least three) $\Delta(54)$ doublets
- Example for "CP made and broken"

Signals of CP-violation

The specific signals of CP-violation are strongly model dependent. We consider as a (toy) example the explicit model of (Carballo-Perez, Peinado, Ramos-Sanchez, 2016)

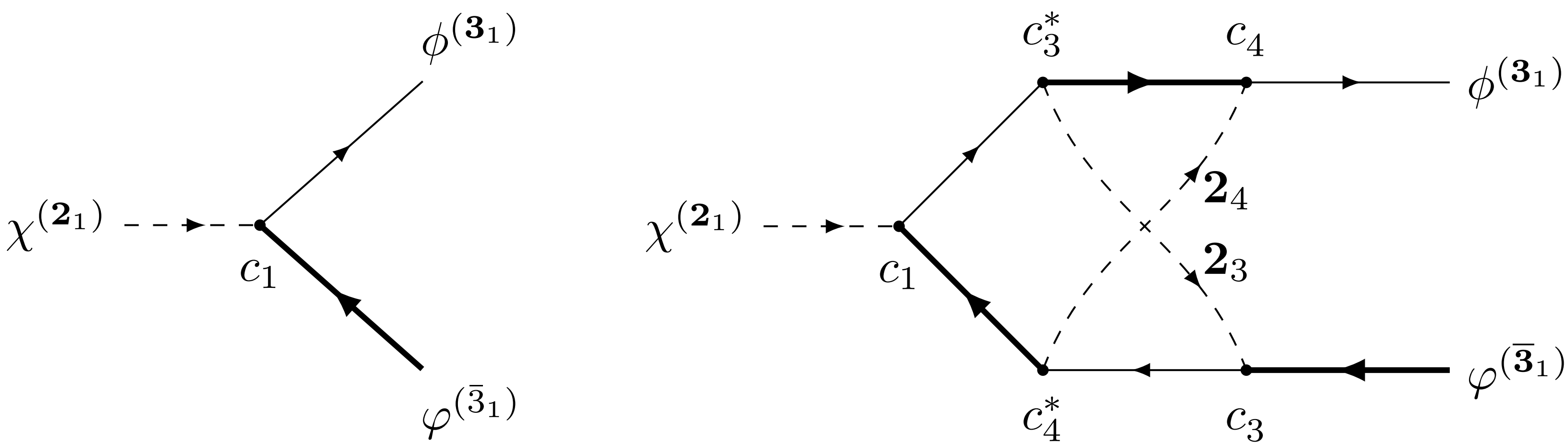
- it contains singlets, triplets and anti-triplets of $\Delta(54)$
- quarks and leptons as triplets
- Higgs as singlet
- right handed neutrinos as anti-triplets
- SM singlets as triplets and anti-triplets

The relevant couplings to the winding modes 2_i are

- $3 \otimes \bar{3} \to 2_i$ and $3 \otimes 3 \otimes 3 \to 2_i \quad (i = 1, 3, 4)$

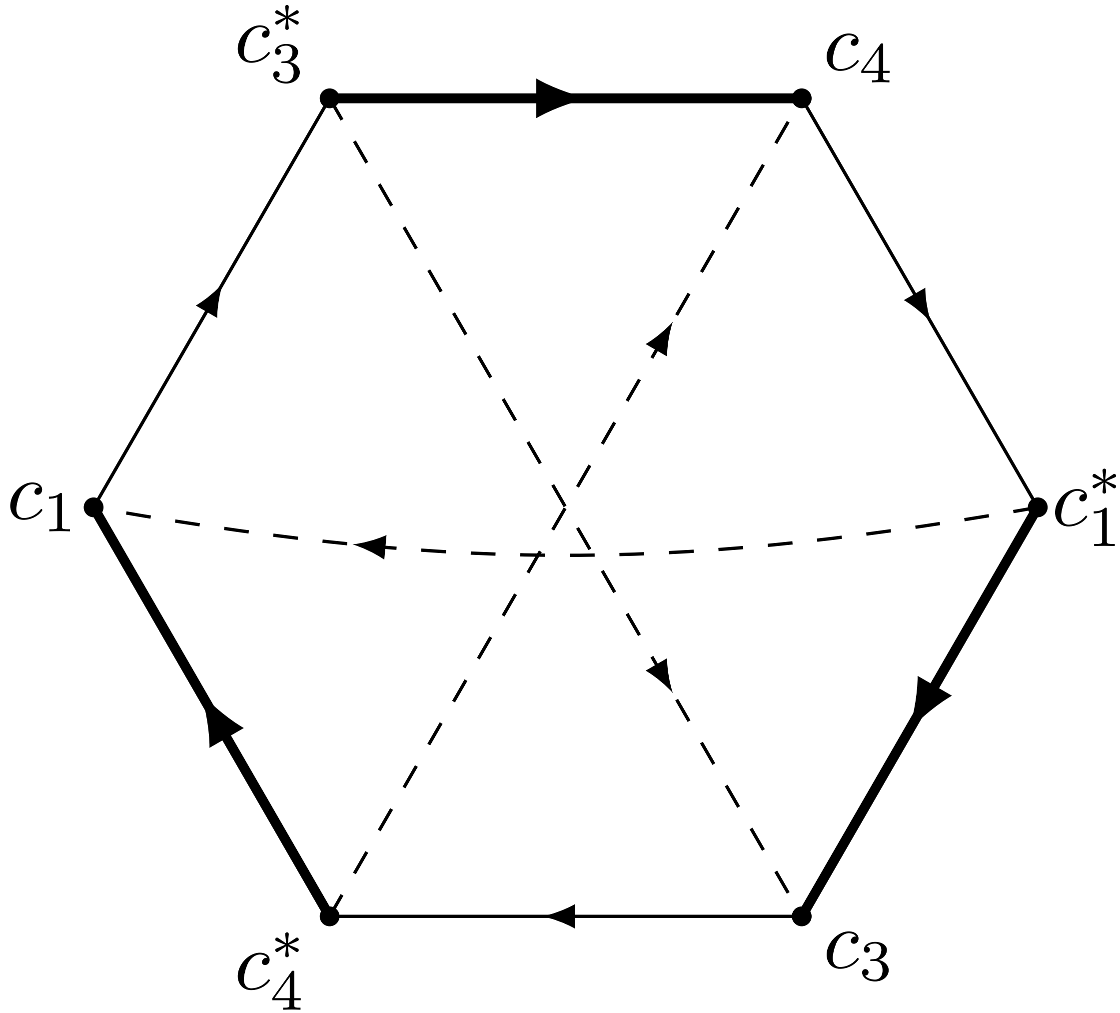
CP violation through decays

CP-violation from the decay of heavy doublets.
All three doublets have to appear in the process.
CP-violation from the interference of two decay diagrams.



- 2_3 and 2_4 in (non-planar) two-loop diagram
- Decay to right-handed neutrinos and SM singlets as source for lepto-genesis

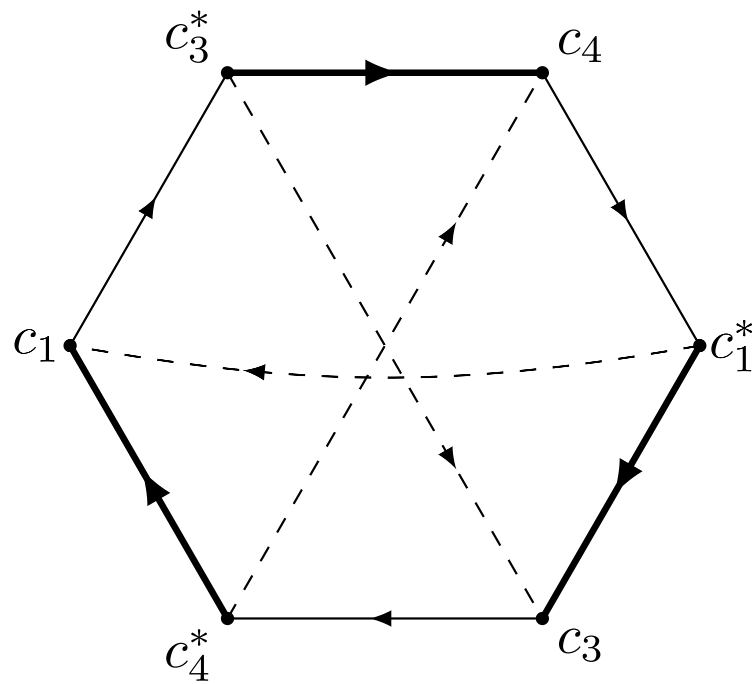
CP-odd basis invariant



CP-violation in physics

The "CP-odd basis invariant" controls all possible CP-violation in physics

- CP-violating decay of heavy doublets
- CP violation in the standard model (Jarlskog determinant)
- QCD Θ-angle



- We need explicit model building to study these effects (coupling of doublets to CKM matrix and Θ_{QCD})

Conclusions

Discussion of CP requires

- the origin of the symmetry ("Make It")
- and its violation ("Break It")

String theory could provide such a mechanism through

- "Explicit geometric CP-violation"
- Unification of flavour symmetry and CP
- CP symmetry for the low energy effective theory
- broken in the presence of heavy winding modes

It provides explicit sources for CP-violating decay of heavy modes, and potentially the CKM phase and Θ_{QCD}

The missing doublet 2_2