Gauge Theories and CP Symmetry

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Global versus Gauge Symmetries

Both types of symmetries are observed in nature

- Global symmetries as a symmetry of physical system
- Local (gauge) symmetry as a "redundancy of description"
- role of anomalies differs in both cases

Global and local symmetries appear in the Standard model of particle physics:

- are gauge symmetries more fundamental?
- are global symmetries necessarily approximate?

Is there a concept of discrete gauge symmetries?

Outline

We want to consider CP as a discrete gauge symmetry. To motivate this we shall discuss

- the relevance of CP symmetry and its breakdown
- the fate of global symmetries
- gobal symmetries in Standard Model of particle physics
- CP as a discrete gauge symmetry
- discrete CP in string theory (as UV-completion)
- an example for CP symmetry and breakdown
- Leptogenesis through decay of heavy particles
- intrinsic sources for Θ angle and Jarlskog determinant

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

Golden age of global symmetries

Once upon a time gobal symmetries were "sacred", e.g.

- Baryon an Lepton number
- discrete symmetries like C, P and T
- we here assume CPT to be exact (thus CP$\sim$T)

It was a kind of "shock" when

- P and C violation were found in the 1950'ties
- and CP violation in the early 1960'ties

Why does nature spoil these beautiful symmetries?

Change of perspective with the rise of the Standard Model!

Standard Model of Particle Physics

In the standard model gauge theories (instead of global symmetries) are of primary importance

- $SU(3)_{QCD} \times SU(2)_W \times U(1)_Y$ as gauge symmetries of strong, weak and electromagnetic interactions
- P and C are "maximally" violated as a consequence of the spectrum of the theory (Weyl-fermions)
- CP and T are broken by Yukawa-couplings of three families of quarks and leptons

Remnant global symmetries as e. g. related to Baryon and Lepton number appear as low energy accidents and are thus an indirect consequence of the gauge symmetries.

Baryon and Lepton number

The global symmetries $U(1)_B$ and $U(1)_L$

- are good symmetries at the renormalizable level, i.e. operators of dimension four (or less than four)

but broken by higher dimensional operators

- $\frac{1}{M}HHLL$ of dimension 5
- neutrino mass as $\frac{<H^2>}{M}$ via "see saw" mechanism
- $\frac{1}{M^2}QQQL$ of dimension 6 (relevant for proton decay)

$U(1)_{B,L}$ are accidental low energy consequences of the gauge symmetries of the standard model.

Role of C, P and T

The relation of C, P and T to gauge theories is more subtle:

- conserved in electromagnetic interactions
- conserved in perturbative QCD but broken by non-perturbative effects related to Θ_{QCD}
- P and C incompatible with spectrum of $SU(2)_W$
- CP violation in Yukawa couplings for at least 3 families of quarks and leptons

"Non-perturbative" topological term in QCD violates T

$$\Theta \epsilon^{\mu\nu\rho\sigma} \mathrm{Tr} F_{\mu\nu} F_{\rho\sigma}$$

leads to electric dipole moment of neutron. This is known as the "strong CP problem" (possible solution via axion)

Paradigm shift from global to local

Today gauge symmetries are of primary importance. Global symmetries are most probably low-energy "accidents" and not exact symmetries.

- $U(1)_{B,L}$ in the standard model are anomalous and broken by non-perturbative effects
- gauge symmetries are anomaly free
- the inflationary universe dilutes all matter. We need B,L-violation (as well as CP-violation) to create a baryon /lepton asymmetry
- black hole evaporation is conjectured to violate all global symmetries (while charges of gauge symmetries are conserved due to presence of gauge-flux).

Characteristics of gauge theories

What is so special about gauge symmetries?

- non-perturbative topological objects like monopoles, strings and branes
- duality symmetries like electric-magnetic duality E.M.
- Aharonov-Bohm effect and flux integrals at infinity

Constraints from quantum gravity

- the role of gauge theories in AdS/CFT correspondence
- spectrum completeness conjecture
- the weak gravity conjecture and the "swampland"

All of these requirements seem to be fulfilled in string theory

The concept of discrete gauge theories

Is there a distinction between global and local discrete symmetries?

- subgroup of continuous gauge symmetry
- subject to anomaly cancellation as well

Concept of discrete gauge symmetry more general

- presence of non-perturbative topological objects
- presence of discrete flux integrals at infinity
- discrete symmetries from higher order gauge fields

Again, string theory can be used as a tool to study these generalized discrete gauge symmetries

CP as a discrete gauge symmetry

CP (violation) is relevant for several phenomena:

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

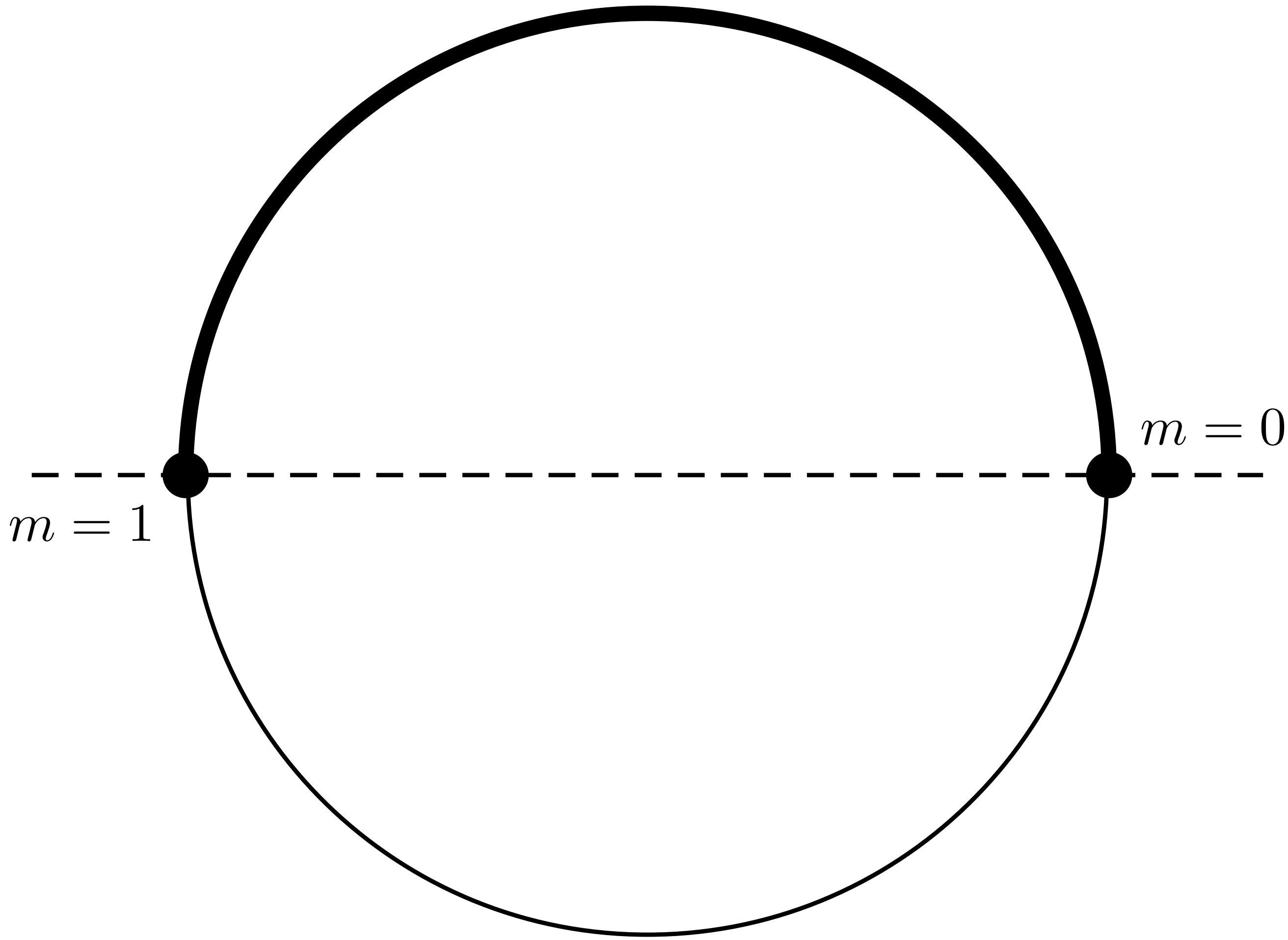
The strong CP-problem requires CP to be a symmetry

- 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?

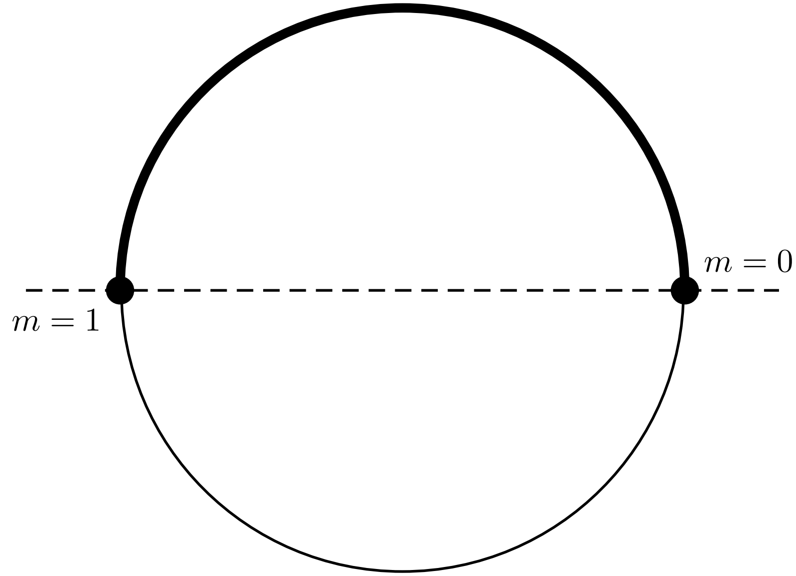
We use string theory for a consistent UV-completion

Interval S_1/Z_2



Discrete symmetry D_4

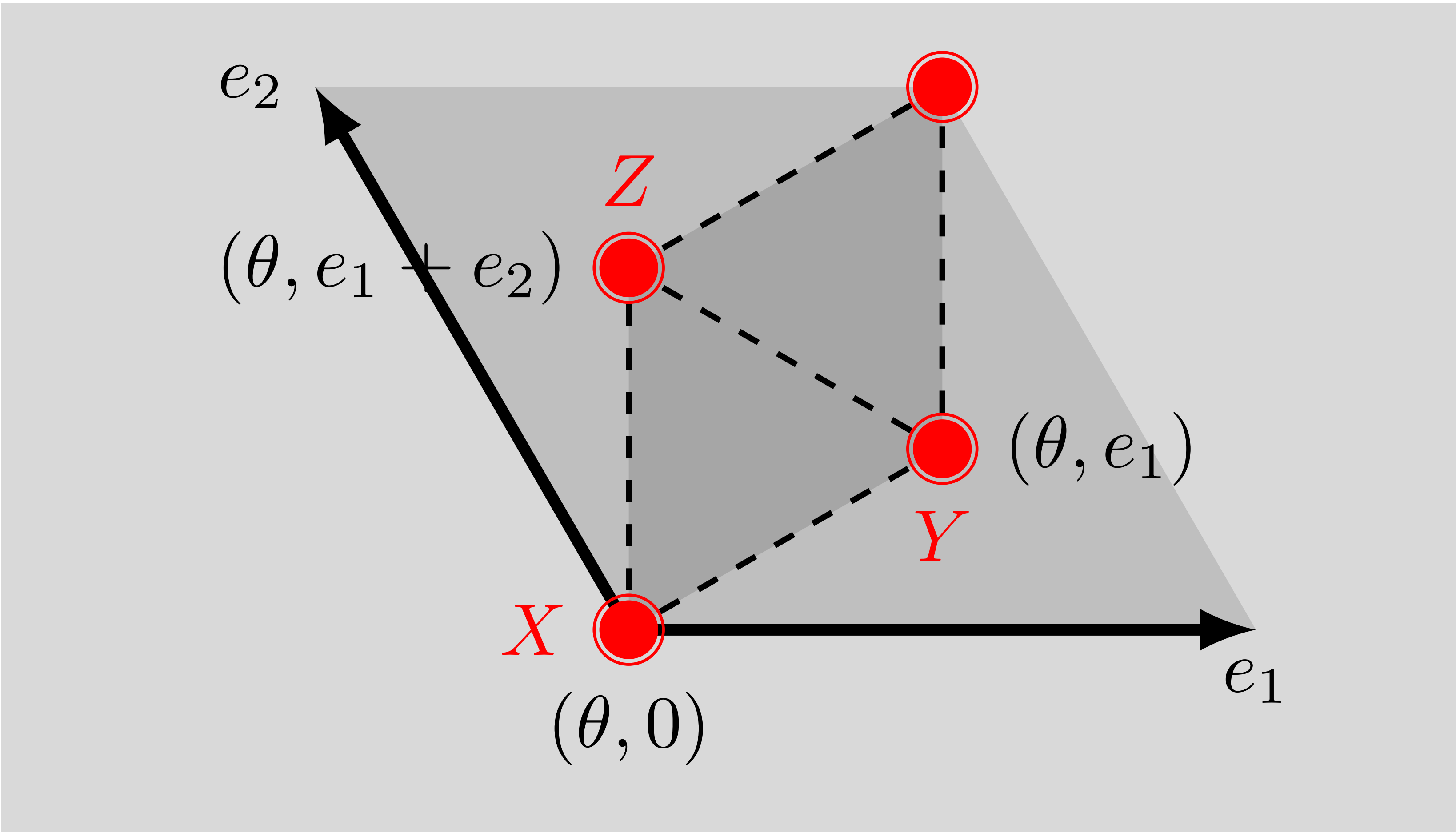
- bulk and brane fields
- S_2 symmetry from interchange of fixed points
- $Z_2 \times Z_2$ symmetry from brane field selection rules



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

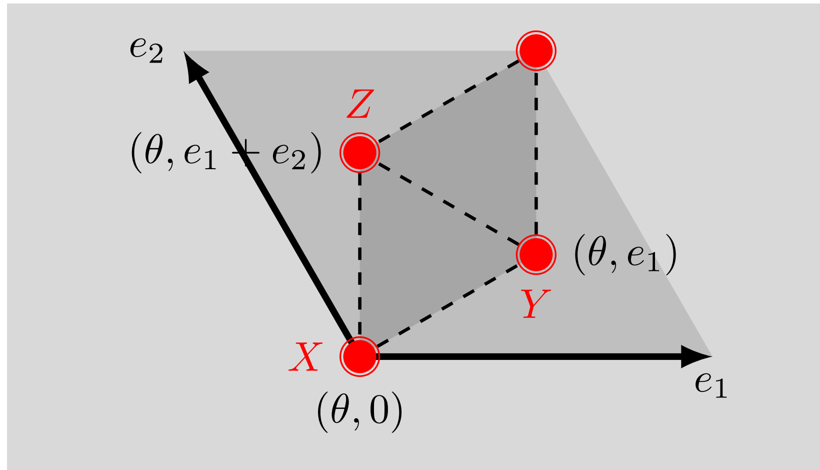
(Kobayashi, Nilles, Ploeger, Raby, Ratz, 2006)

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 non-abelian 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 non-abelian 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 the 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 $(rep)^*$

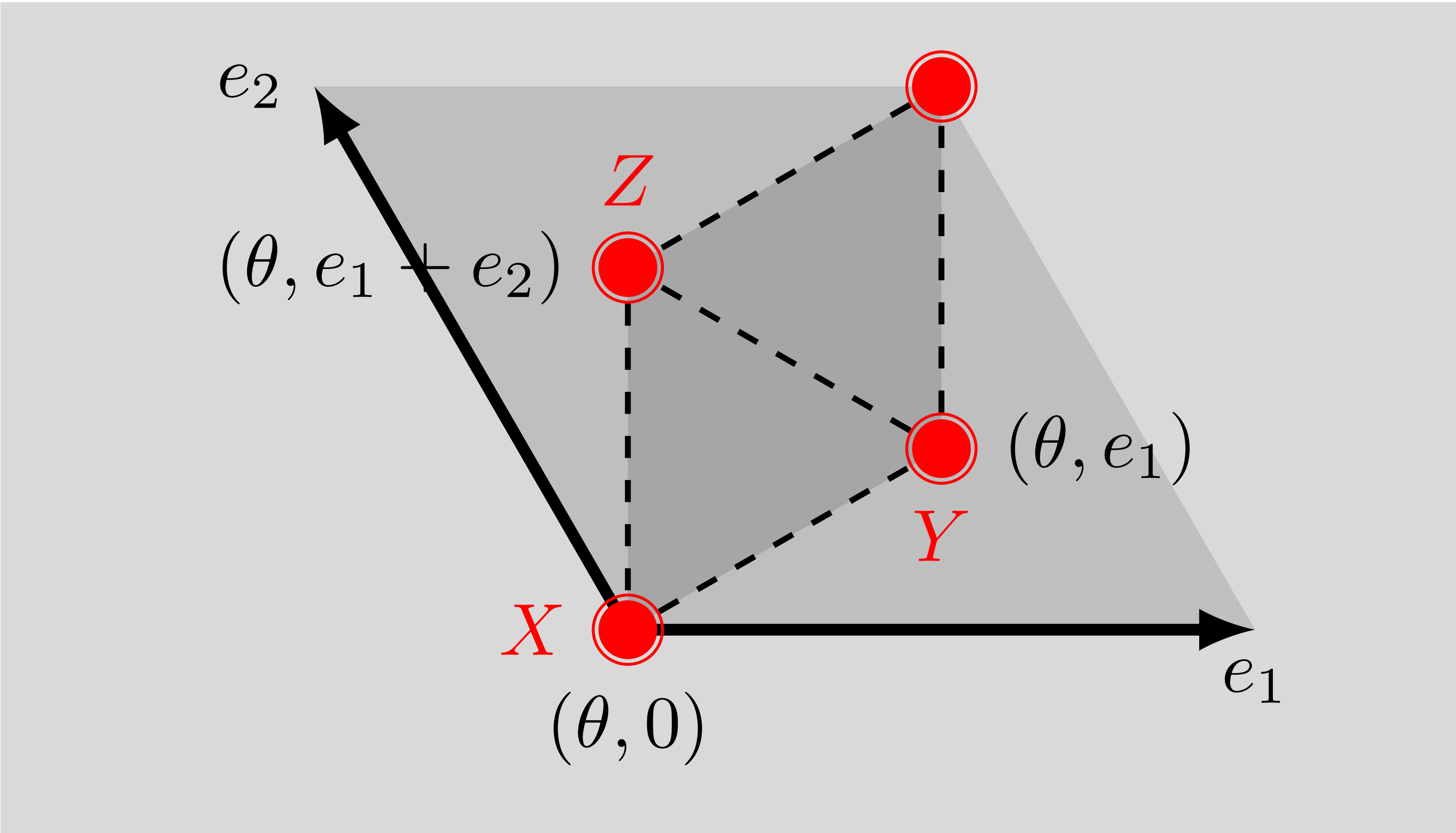
This gives an intimate relation of flavour and CP symmetry

- 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

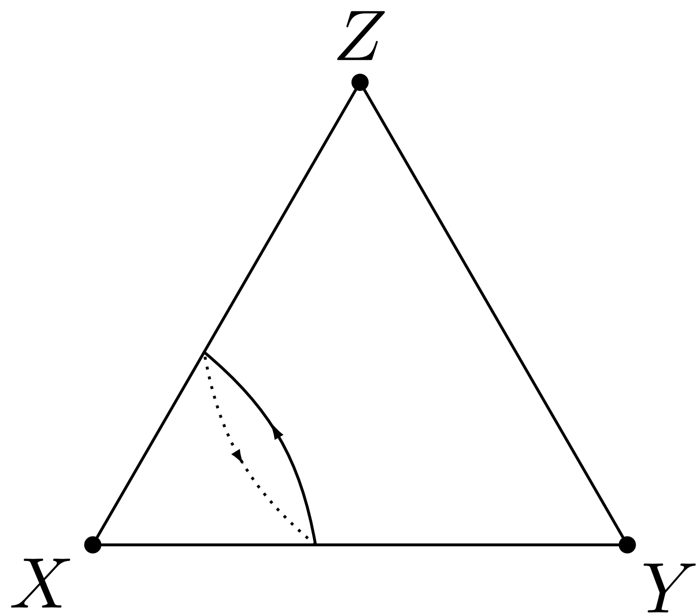
- untwisted states closed on the 2d plane
- winding states $(1, e_i)$ closed on the torus
- twisted states (θ, e_i) closed on the orbifold

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



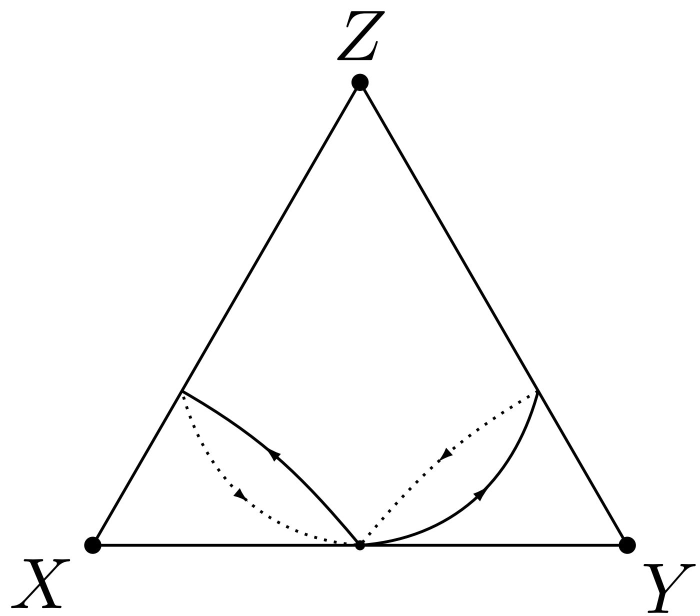
CP maps triplets (anti-triplets) to their complex conjugates

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 winding 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 automorphisms 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 can arise 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)

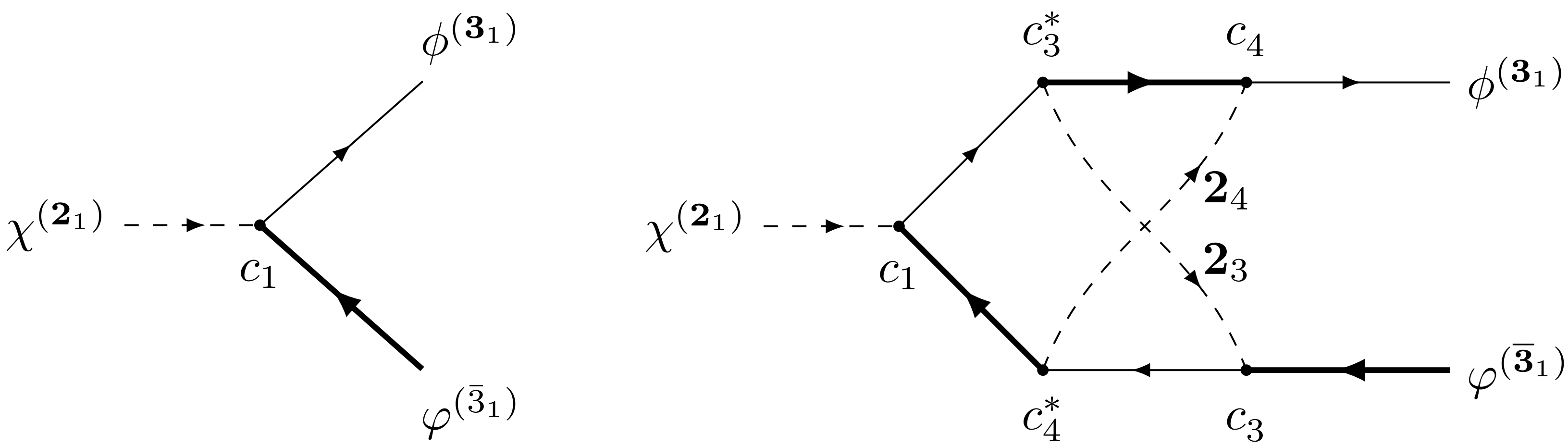
- it contains singlets, triplets and anti-triplets of $\Delta(54)$
- quarks and leptons as triplets
- Higgs as singlet
- right handed neutrinos as anti-triplets
- SM singlets as triplets and anti-triplets

The relevant couplings to the winding modes 2_i are

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

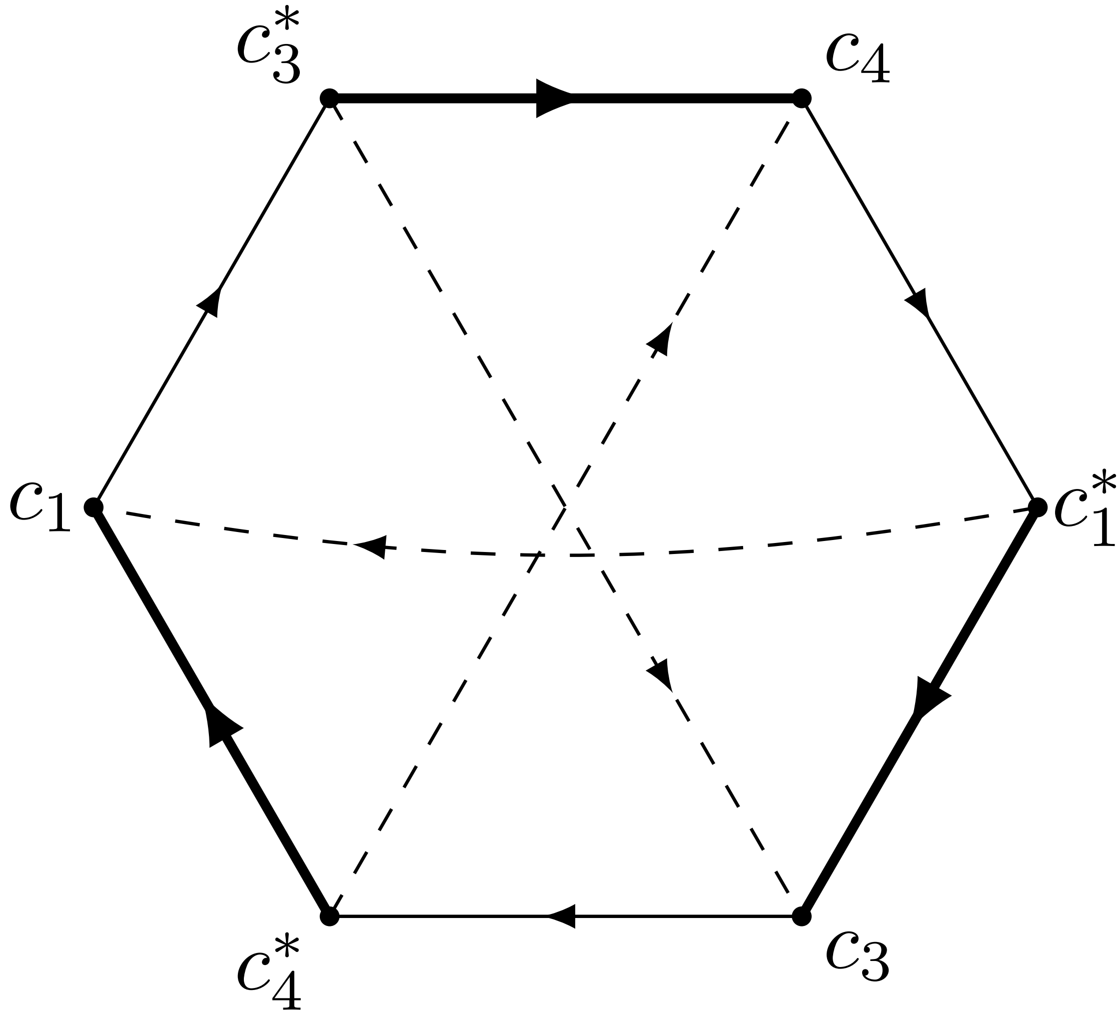
CP violation through decays

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

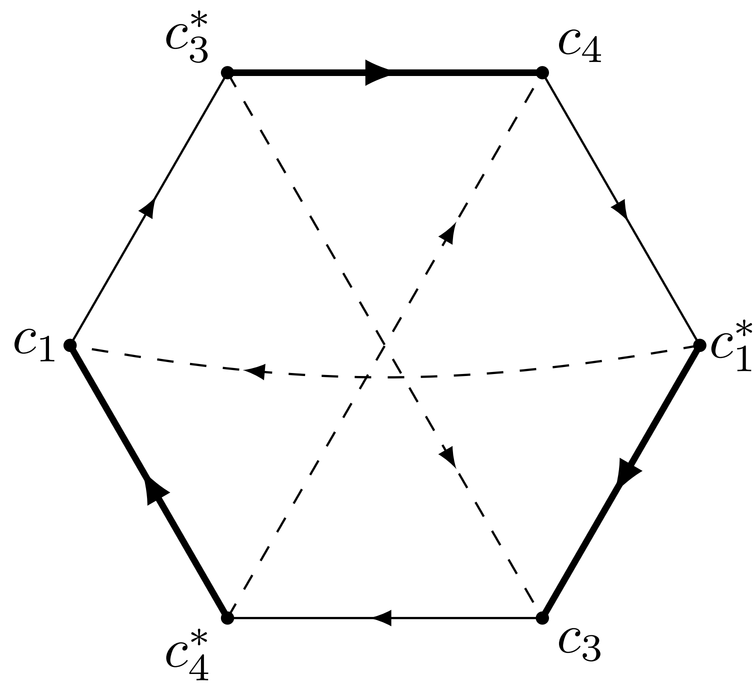
CP-odd basis invariant



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 particles, and potentially the CKM phase and Θ_{QCD}