Anomalous U(1)´s, Chern-Simons couplings and the Standard Model

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Work in collaboration with: Massimo Bianchi, Emilian Dudas, Elias Kiritsis.
• Anomalous U(1)’s are a generic prediction of all open string models (possible candidates to describe Standard Model).

• The anomaly is cancelled via Green-Schwarz-Sagnotti mechanism, and the anomalous U(1)’s become massive.

• However, generalized Chern-Simons couplings are necessary to cancel all the anomalies.

• These Chern-Simons terms provide new signals that distinguish such models from other Z’-models.

• Such couplings may have important experimental consequences.
Anomalous U(1)s

Consider a chiral gauge theory:

\[ \delta \mathcal{L}_{\text{1-loop}} = \epsilon \, \zeta \, \text{Tr}[G \wedge G] \]

If \( \zeta = \text{Tr}[QT^a T^a] \neq 0 \), the U(1) is anomalous and gauge symmetry is broken due to the 1-loop diagram:

Therefore under \( A_\mu \rightarrow A_\mu + \partial_\mu \epsilon \):

To cancel the anomaly we add an axion:

\[ \delta \mathcal{L}_{\text{axion}} = -\epsilon \, \zeta \, \text{Tr}[G \wedge G] \]

which also transforms as: \( a \rightarrow a - M \epsilon \), therefore: and the anomaly is cancelled.
Anomalous U(1)′s are massive

- The axion which mixes with the anomalous U(1)′s is a bulk field emerging from the twisted RR sector.
- The term that mixes the axion with the U(1) gives mass to the gauge boson and breaks the U(1) symmetry:
  \[ \frac{1}{2} (\partial_\mu a + M A_\mu)^2 \]
- The UV mass can be computed from a string 1-loop diagram and is given by the UV contact term:
- The masses are of order or even smaller of the string scale.

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Consider now the presence of an additional non-anomalous $U(1)$ $Y^\mu$. By definition, this means that:

$$\text{Tr}[Y] = \text{Tr}[Y^3] = \text{Tr}[Y \ T^a T^a] = 0$$

However, there might be mixed anomalies due to the traces:

$$\text{Tr}[Q^3] = c_3 \ , \ \text{Tr}[Q^2 Y] = c_2 \ , \ \text{Tr}[Q Y^2] = c_1 \ , \ \text{Tr}[Q T^a T^a] = \xi$$

Diagrams of the following type:

break the gauge symmetries: $A_\mu \to A_\mu + \partial_\mu \epsilon$ , $Y_\mu \to Y_\mu + \partial_\mu \zeta$

$$\delta \mathcal{L}_{1\text{-loop}} = \epsilon \left[ \frac{c_3}{3} F^A \wedge F^A + c_2 \ F^A \wedge F^Y + c_1 \ F^Y \wedge F^Y + \xi \ \text{Tr}[G \wedge G] \right]$$

$$+ \zeta \left[ c_2 \ F^A \wedge F^A + c_1 \ F^A \wedge F^Y \right]$$
The need of Chern-Simons terms

\[ \delta \mathcal{L}_{1\text{-loop}} = \epsilon \left[ \frac{c_3}{3} F^A \wedge F^A + c_2 F^A \wedge F^Y + c_1 F^Y \wedge F^Y + \xi \mathrm{Tr}[G \wedge G] \right] \]

\[ + \zeta \left[ c_2 F^A \wedge F^A + c_1 F^A \wedge F^Y \right] \]

To cancel the anomalies we add axions as before:

\[ \mathcal{L}_{\text{class}} \sim -\frac{1}{4g^2} (F^A)^2 - \frac{1}{4g_Y^2} (F^Y)^2 + \frac{1}{2} (\partial_\mu a + M A_\mu)^2 \]

\[ + D_0 a \mathrm{Tr}[G \wedge G] + D_1 a F^A \wedge F^A + D_2 a F^A \wedge F^Y + D_3 a F^Y \wedge F^Y \]

However, the axionic transformation \( a \rightarrow a - M \epsilon \) does not cancel all the anomalies. The above action is \( Y^\mu \)-gauge invariant.

We need non-invariant terms: Generalized Chern – Simons.
Chern-Simons terms

We need non-invariant terms:

\[ \mathcal{L}_{CS} = D_4 Y \wedge A \wedge F^A - D_5 A \wedge Y \wedge F^Y \]

Now, a combination of the axionic and the GCS-terms cancel the anomalies:

\[ \delta \mathcal{L}_{1\text{-loop}} = \epsilon \left[ \frac{c_3}{3} F^A \wedge F^A + c_2 F^A \wedge F^Y + c_1 F^Y \wedge F^Y + \xi \text{Tr}[G \wedge G] \right] \]

\[ + \zeta \left[ c_2 F^A \wedge F^A + c_1 F^A \wedge F^Y \right] \]

To cancel the anomalies we obtain:

\[ D_0 = \xi , \quad D_1 = \frac{c_3}{3} , \quad D_2 = 2c_2 , \quad D_3 = 2c_1 , \quad D_4 = c_2 , \quad D_5 = c_1 \]

The anomalies fix the coefficients of the GCS-terms in the effective action.
Consider the general Lagrangian:

\[ \mathcal{L} = - \sum_i \frac{1}{4g_i^2} F_i^2 - \sum_a \frac{1}{4g_a^2} G_a^2 + \text{chiral fermions} \]

It is easy to show that:  \( E \sim \)
General Anomaly Cancellation

Requiring gauge invariance under \( A^i_\mu \rightarrow A^i_\mu + \partial_\mu \epsilon^i \) and \( a^I \rightarrow a^I - M^I_\epsilon^i \) the anomaly cancellation conditions are:

\[ \sum_I M^I_i C^I_{ijk} + 2E^I_{ijk} = A^I t_{ijk}, \quad \sum_I M^I_i D_{Ia} = B^I t_{ia} \]

Special Cases:
- No fermions.
- Only one anomalous U(1).
String Computation of GCS

\[ M_{i(a)}^{k,f} \sim tr_a[\gamma^k \lambda_i] \]

\[ C_{ij(a)}^{k,f} \sim tr_a[\gamma^k \lambda_i \lambda_j] \]

The GCS-terms are:

\[ E^{(a)}_{ijk} = - \sum_{r,f} M_{i(a)}^{r,f} C_{ij}^{r,f} \neq 0 \]

Example: \( Z_6 \) Orientifold: \([U(6)^2 \times U(4)]_9 \times [U(6)^2 \times U(4)]_5\)

- **Non-zero GCS are needed:** 1
- \( E_{ij} \)

\[
\begin{pmatrix}
0 & 36 & -72 & 36 & 0 & -24 \\
-36 & 0 & 72 & 0 & 36 & 24 \\
24 & -24 & 0 & 36 & -72 & 0 \\
36 & 0 & -24 & 0 & 72 & 0 \\
0 & -36 & 24 & -36 & 0 & 72 \\
24 & -24 & 0 & 24 & -24 & 0 \\
\end{pmatrix}
\]

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Heavy Fermions

- **GCS-terms** are also a prediction of an anomaly-free chiral gauge theory with heavy and light fermions (after SSB).

- Denoting the heavy mass-insertion with (\(\times\)): example:
Phenomenological implications

• A typical D-brane description of the Standard Model:

\[ SU(3) \times SU(2) \times U(1)_Y \]

\[ SU(3) \times SU(2) \times U(1) \times U(1) \times U(1) \]

• There are three more abelian gauge bosons.

• These U(1)’s are anomalous.
A low string scale model

- Higgses are charged under $Y$ and $PQ$ but not under $B$ and $L$.

- After EW symmetry breaking, both $Y$ and $PQ$ are spontaneously broken.

- Two origins for masses:
  1. The UV mass matrix of the anomalous U(1)s: $\sim M_s$.
  2. The Higgs mechanism: $\nu_H \sim 100-200$ GeV.
Z-Z′ Mixings

• We go to the photon basis:

\[
\begin{pmatrix}
W^3 \\
Y \\
PQ
\end{pmatrix}
= 
\begin{pmatrix}
c_{11} & c_{12} & c_{13} \\
c_{21} & c_{22} & c_{23} \\
c_{31} & c_{32} & c_{33}
\end{pmatrix}
\begin{pmatrix}
A \\
Z^0 \\
Z'
\end{pmatrix}
\]

• The coefficients are:

\[c_{11}, c_{12}, c_{21}, c_{22}, c_{33} \sim \mathcal{O}(1)\, , \, c_{13}, c_{23}, c_{31}, c_{32} \sim \mathcal{O}\left(\frac{M_Z^2}{M_S^2}\right) \sim 10^{-4}\]
**CS Couplings and LHC**

- Consider the various anomaly canceling GCS-terms:

  \[
  \begin{align*}
  Z^0 \wedge A \wedge dA & \Rightarrow Z^0 \rightarrow \gamma \gamma \sim \mathcal{O}\left(\frac{M_Z^2}{M^2}\right), \\
  A \wedge Z^0 \wedge dZ^0 & \Rightarrow Z^0 \rightarrow Z^0 \gamma \sim \mathcal{O}\left(\frac{M_Z^2}{M_s^2}\right), \\
  Z' \wedge A \wedge dA & \Rightarrow Z' \rightarrow \gamma \gamma \sim \mathcal{O}(1), \\
  Z' \wedge Z^0 \wedge dZ^0 & \Rightarrow Z' \rightarrow Z^0 Z^0 \sim \mathcal{O}(1), \\
  Z' \wedge Z^0 \wedge dA & \Rightarrow Z' \rightarrow Z^0 \gamma \sim \mathcal{O}(1)
  \end{align*}
  \]

- Some terms are zero on-shell.
- Therefore, new signals may be visible in LHC, like:

  \[ pp \rightarrow Z' \rightarrow \gamma Z^0 \]
Conclusions

• Anomalous U(1)’s are a generic prediction of orientifold vacua.

• If the string scale is low (few TeV region) such gauge bosons become the tall-tales signals of such vacua.

• Anomaly related Chern Simons-like couplings produce new signals that distinguish such models from other Z’-models.

• Such signals may be visible in LHC.