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

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Content of this lecture

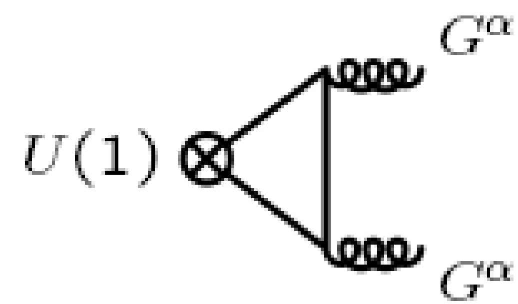
- Anomalous U(1)´s are a generic prediction of all open string models (possible candidates to describe Standard Model).
- The anomaly is cancelled via Green-Schwarz-Sagnotti mechanism, and the anomalous U(1)´s become massive.
- However, generalized Chern-Simons couplings are necessary to cancel all the 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:

$$\Longrightarrow \quad \delta\mathcal{L}_{1-loop} = \epsilon\ \zeta\ Tr[G \wedge G]$$

If $\zeta = Tr[QT^aT^a] \neq 0$, the U(1) is anomalus and gauge symmetry is broken due to the 1-loop diagram:



Therefore under $A_\mu \to A_\mu + \partial_\mu \epsilon$:

To cancel the anomaly we add an axion:

$$\Longrightarrow \quad \delta\mathcal{L}_{axion} = -\epsilon\ \zeta\ Tr[G \wedge G]$$

which also transforms as: $a \to a - M\ \epsilon$, therefore:

and the anomaly is cancelled.

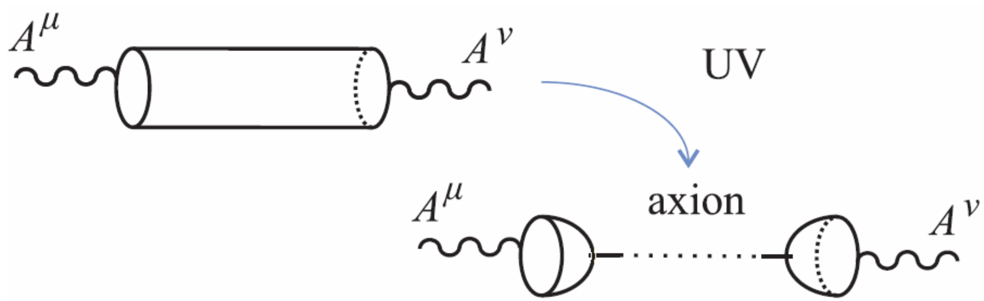
Anomalous U(1)´s are massive

- 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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Presence of non-anomalous U(1)´s

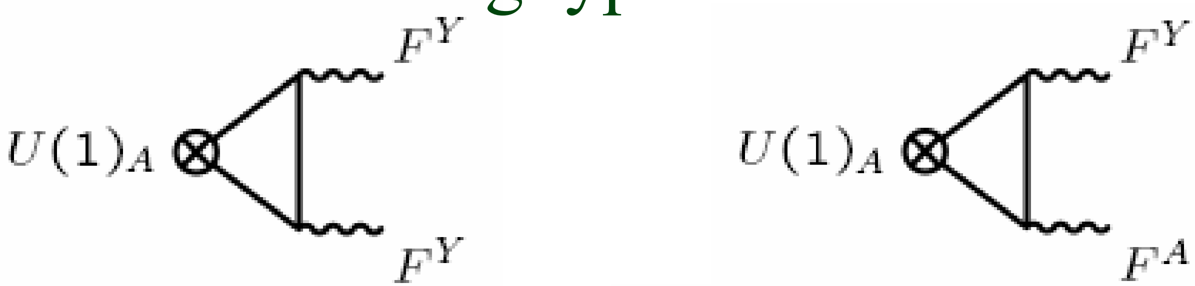
Consider now the presence of an additional non-anomalous U(1) Y^μ. By definition, this means that:

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

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

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

Diagrams of the following type:



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

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

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

The need of Chern-Simons terms

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

$$+\zeta\left[c_2\ F^A\wedge F^A + c_1\ F^A\wedge F^Y\right] \longleftarrow \quad ?$$

To cancel the anomalies we add axions as before:

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

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

However, the axionic transformation $a \to a - M\epsilon$ does not cancel all the anomalies. The above action is Y^μ-gauge invariant.

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

Chern-Simons terms

We need non-invariant terms:

the variation the variation

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

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

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

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

To cancel the anomalies we obtain:

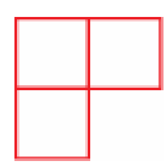
$$D_0 = \xi\ , \quad D_1 = \frac{c_3}{3}\ , \quad D_2 = 2c_2\ , \quad D_3 = 2c_1\ , \quad D_4 = c_2\ , \quad D_5 = c_1$$

The anomalies fix the coefficients of the GCS-terms in the effective action.

The General Case

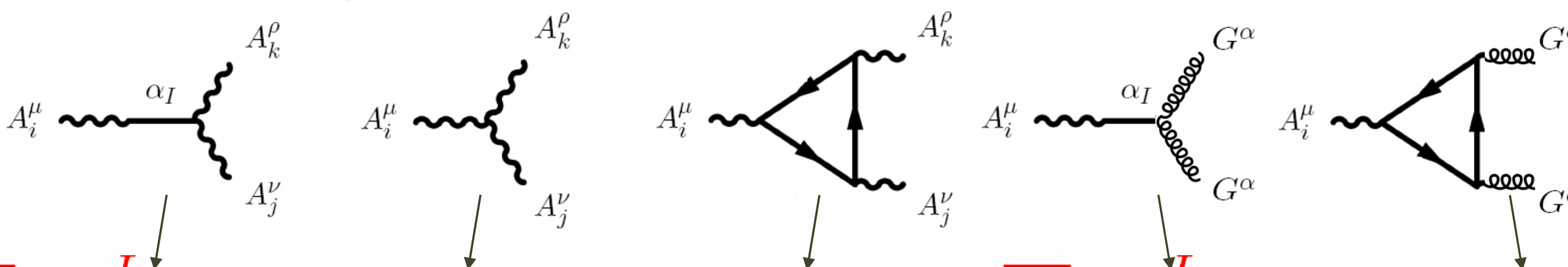
Consider the general Lagrangian:

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

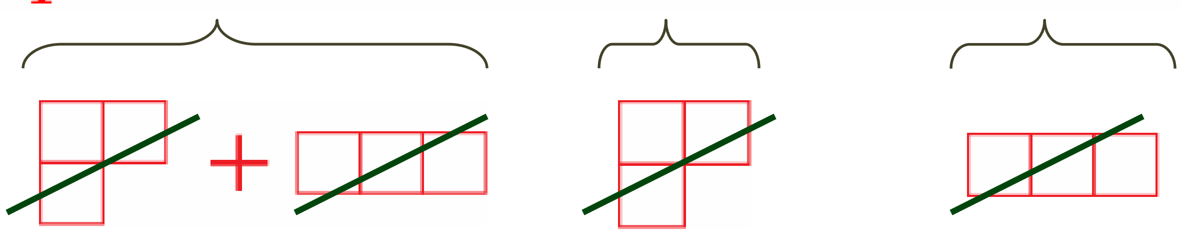
It is easy to show that: $E \sim$ 

General Anomaly Cancellation

Requiring gauge invariance under $A^i_\mu \to A^i_\mu + \partial_\mu \epsilon^i$ and $a^I \to a^I - M^I_i \epsilon^i$ the anomaly cancellation conditions are:



$$\sum_I M^I_i C_{Ijk} + 2E_{ijk} = A\ t_{ijk} \quad , \quad \sum_I M^I_i D_{Ia} = B\ t_{ia}$$

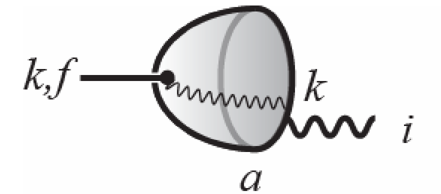


Special Cases:

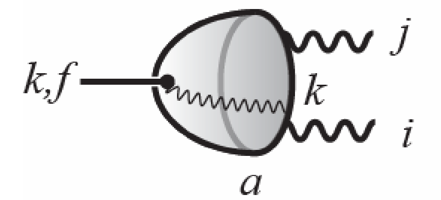
- No fermions.
- Only one anomalous U(1).

String Computation of GCS

$$M^{k,f}_{i(a)} \sim tr_a[\gamma^k \lambda_i]$$ ⟵



$$C^{k,f}_{ij(a)} \sim tr_a[\gamma^k \lambda_i \lambda_j]$$ ⟵



The GCS-terms are:

$$E^{(a)}_{[ij]k} = -\sum_{r,f} M^{r,f}_{[i(a)}\, C^{r,f}_{j]k(a)} \neq 0$$

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

- Non-zero GCS are needed: $E_{ijj} \to$

- There are: $\begin{cases} \text{2 non-anomalous} \\ \text{4 anomalous} \end{cases}$ $\sim \begin{cases} 1 \\ 5 \end{cases} \begin{pmatrix} 0 & 36 & -72 & 36 & 0 & -24 \\ -36 & 0 & 72 & 0 & -36 & 24 \\ 24 & -24 & 0 & 24 & -24 & 0 \\ 36 & 0 & -24 & 0 & 36 & -72 \\ 0 & -36 & 24 & -36 & 0 & 72 \\ 24 & -24 & 0 & 24 & -24 & 0 \end{pmatrix}$

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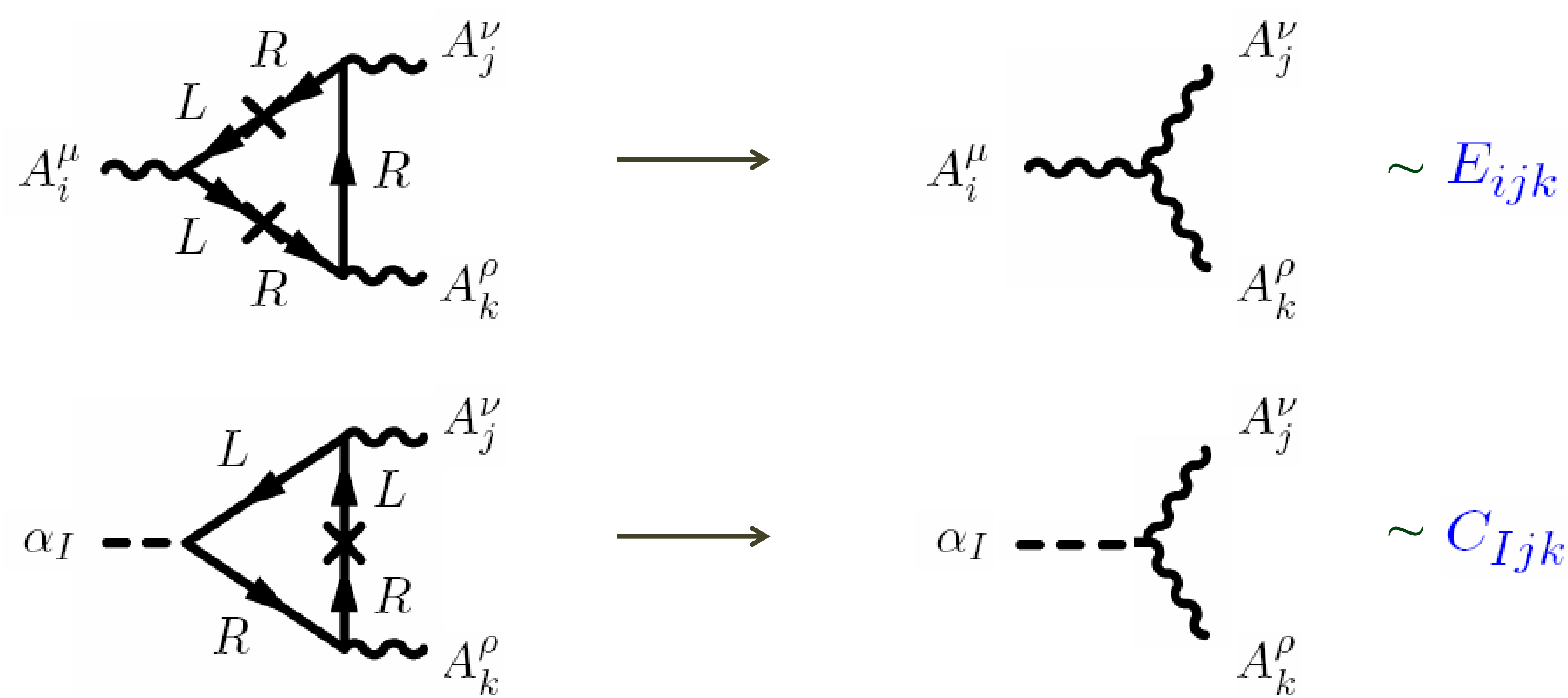
Heavy Fermions

- 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 (×): example:

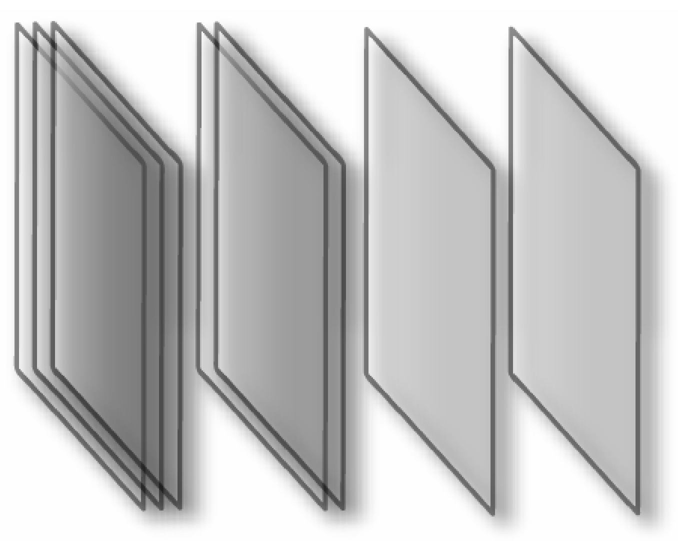


Phenomenological implications

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

Standard Model

$$SU(3)\times SU(2)\times U(1)_Y$$



$$SU(3)\times SU(2)\times U(1)_3\times U(1)_2\times U(1)\times U(1)'$$

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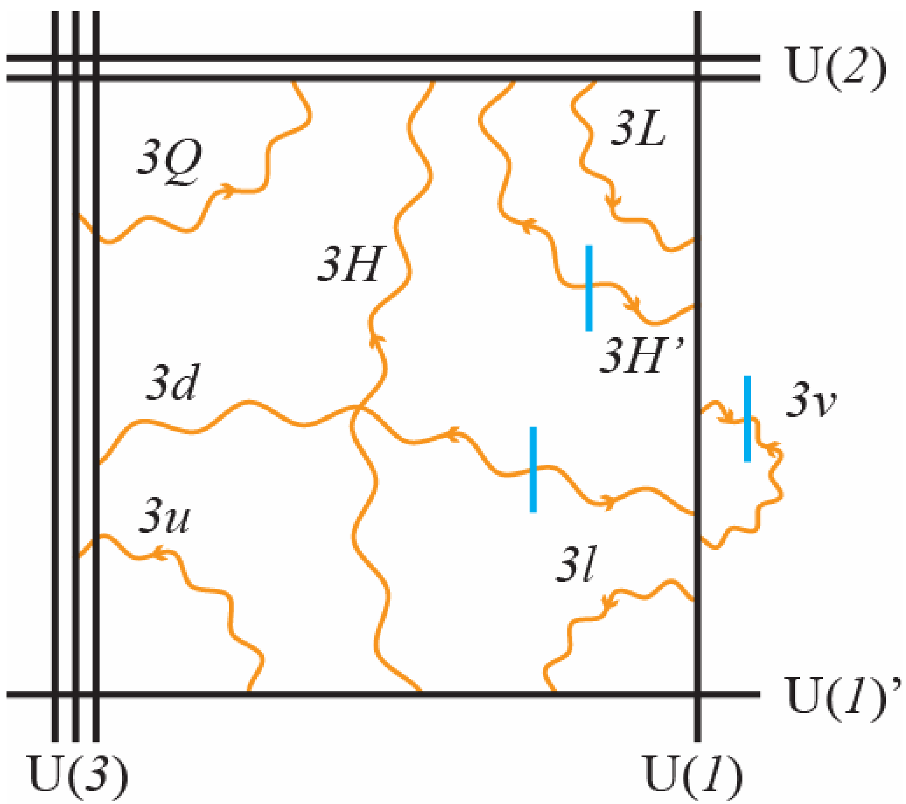
- There are three more abelian gauge bosons.
- These U(1)′s are anomalous.

A low string scale model



Hypercharge	$Y = -\frac{1}{3}Q_3 - \frac{1}{2}Q_2 + Q_1$
Lepton Number	$L = \frac{1}{2}(Q_3 + Q_2 - Q_1 - Q_1')$
Peccei – Quinn	$PQ = -\frac{1}{2}(Q_3 - Q_2 - 3Q_1 - 3Q_1')$

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- 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: $v_H \sim 100\text{-}200$ 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:

$$c_{11}, c_{12}, c_{21}, c_{22}, c_{33} \sim \mathcal{O}(1) \quad , \quad c_{13}, c_{23}, c_{31}, c_{32} \sim \mathcal{O}\left(\frac{M_Z^2}{M_s^2}\right) < 10^{-4}$$

CS Couplings and LHC

- Consider the various anomaly canceling GCS-terms :

$$
PQ \wedge Y \wedge dY \longrightarrow \begin{cases}
Z^0 \wedge A \wedge dA & \Rightarrow & Z^0 \to \gamma\gamma & \sim & \mathcal{O}\left(\frac{M_Z^2}{M_s^2}\right), \\
A \wedge Z^0 \wedge dZ^0 & \Rightarrow & Z^0 \to Z^0\gamma & \sim & \mathcal{O}\left(\frac{M_Z^2}{M_s^2}\right), \\
Z' \wedge A \wedge dA & \Rightarrow & Z' \to \gamma\gamma & \sim & \mathcal{O}(1), \\
Z' \wedge Z^0 \wedge dZ^0 & \Rightarrow & Z' \to Z^0 Z^0 & \sim & \mathcal{O}(1), \\
Z' \wedge Z^0 \wedge dA & \Rightarrow & Z' \to Z^0\gamma & \sim & \mathcal{O}(1)
\end{cases}
$$

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

$$pp \to Z' \to \gamma Z^0$$

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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.