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Minimal Anomalous U(1) Extension of the MSSM

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Based on works with:

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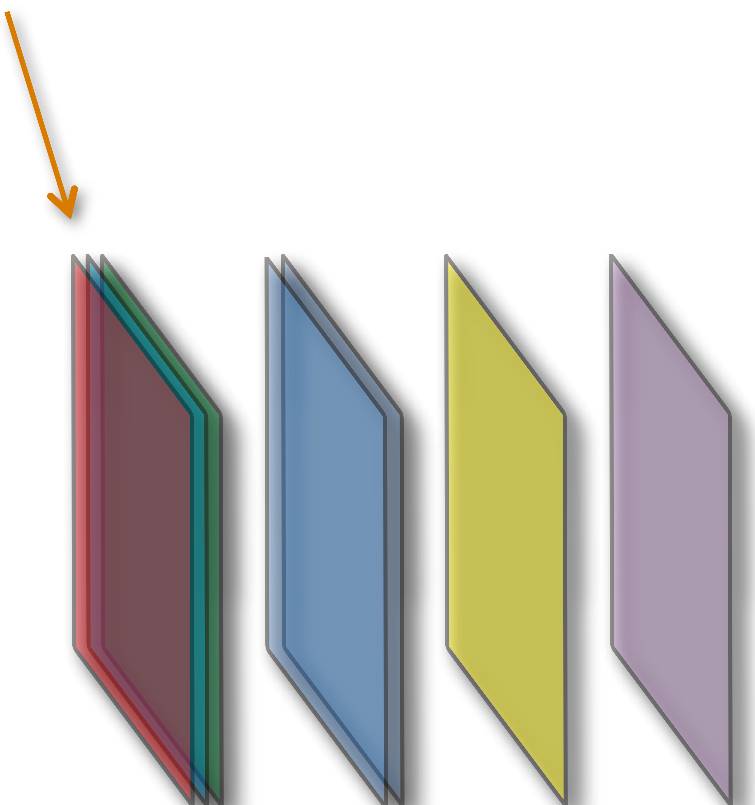
Plan of the talk

- Introduction
- Anomalous U(1)´s
- Generalized Chern-Simons terms
- Anomalous U(1) extension of the MSSM
- Decays and LHC
- Conclusions

Typical D-brane Standard Models

- In open string vacua the Standard Model is located on some stacks of branes (intersecting or not):



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

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

Aldazabal Ibanez Marchesano Quevedo Rabadan Uranga,
Antoniadis Kiritsis Tomaras Rizos,
Cvetic Shiu Blumenhagen Honecker Kors Lust Ott,
Schellekens Dijkstra Huiszoon et al..

Standard Model with many U(1)´s

- Up to now, there is no D-brane model that successfully describes all the characteristics of the Standard Model. We are working on this…

- However, if there is such D-brane model then it predicts several U(1)´s (as many as the number of the stack of D-branes that participate).

- From these U(1)´s:

  - One is the Hypercharge (massless and anomaly-free)

  - The rest are typically superficially anomalous (?!)

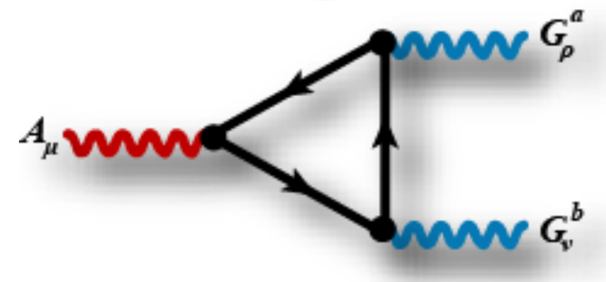
Anomalous U(1)´s

Consider a chiral gauge theory:

$$\mathcal{L} = -\frac{1}{4g_A^2}F^2 - \frac{1}{4g_G^2}Tr[G^2] + chiral\ fermions$$

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

If $\zeta = Tr[QT^aT^a] \neq 0$, 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:

$$\mathcal{L}_{axion} = \frac{1}{2}(\partial_\mu a + MA_\mu)^2 + \frac{\zeta}{M}\, a\, Tr[G \wedge G]$$

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

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

and the anomaly is cancelled.

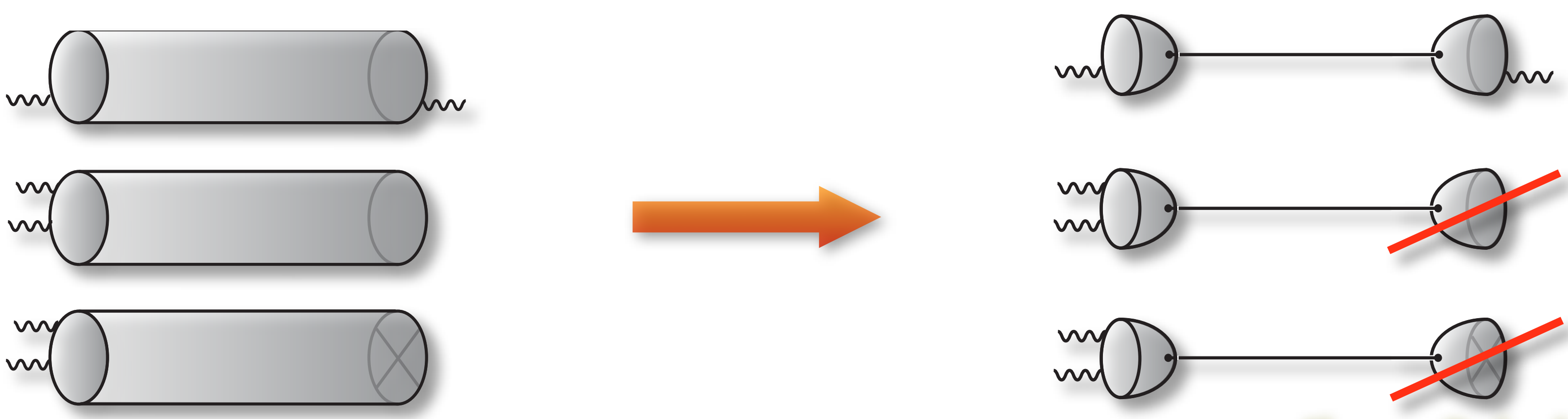
Green-Schwarz
Sagnotti

Anomalous U(1)´s are massive

- The axion which mixes with the anomalous U(1)´s is a field emerging from the closed string sector (twisted RR field).

- The U(1)'s become massive due to the couplings with the axion:

- These UV mass-term has been computed from a string 1-loop diagram:



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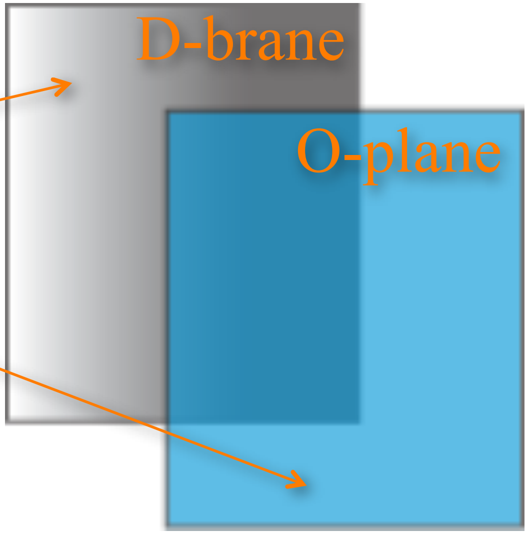
Antoniadis Kiritsis Rizos
Anastasopoulos

Anomalous U(1)´s and F-I terms

- The masses of the anomalous U(1)s are proportional to the internal volumes. If "D" the brane where the U(1) is attached and "P" the O-plane where the axion is localized:

$$M_{phys}^2 = g^2 M_s^2 \sim \frac{M_s^2}{V_{D-D\cap P} V_{P-D\cap P}}$$



- There are D-term like potentials of the form:

$$V \sim \left(s + \sum_i q_i \phi_i^2 \right)^2$$

where s is a bulk modulus. In SUSY models, they are the chiral partners of the axions. If we are on the O-pane, $\langle s \rangle = 0$ and the global U(1) symmetry remains intact.

Poppitz

Hypercharge & anomalous U(1)´s

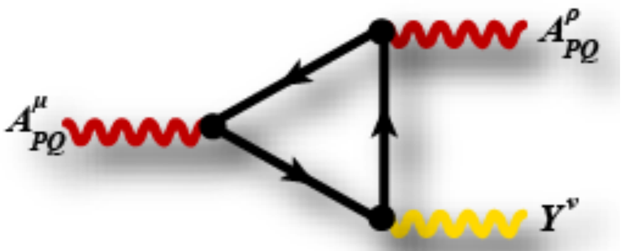
For the Hypercharge Y^μ, we have:

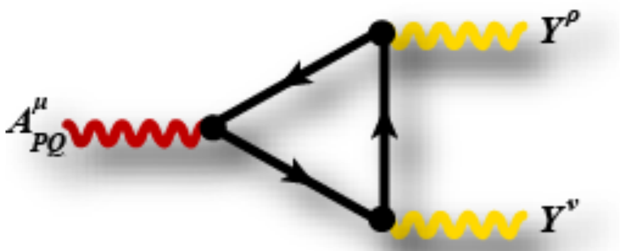
$$Tr[Y] = Tr[Y^3] = Tr[YT^aT^a] = 0$$

However, there might be mixed anomalies of Y^μ with the anomalous U(1)´s (ex: the Peccei-Quinn A^μ_{PQ}) due to:

$$Tr[Q^3] = c_3 \qquad Tr[Q^2Y] = c_2 \qquad Tr[QY^2] = c_1 \qquad Tr[QT^aT^a] = \xi$$

These diagrams:





break the gauge symmetries: $\quad A^\mu_{PQ} \to A^\mu_{PQ} + \partial^\mu \epsilon \quad Y^\mu \to Y^\mu + \partial^\mu \zeta$

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

Axionic terms are not enough

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

$$+\zeta\Big[c_2 F^{PQ}\wedge F^{PQ} + c_1 F^{PQ}\wedge F^{Y}\Big] \longleftarrow \;?$$

To cancel the anomalies we add axions as before:

$$\mathcal{L}_{class} \sim -\frac{1}{4g_{PQ}^2}F_{PQ}^2 - \frac{1}{4g_Y^2}F_Y^2 + \frac{1}{2}(\partial^\mu a + M\ A^\mu_{PQ})^2$$

$$+\cancel{D_0\ a\ Tr[G\wedge G]} + \cancel{D_1\ a\ F^{PQ}\wedge F^{PQ}} + \cancel{D_2\ a\ F^{PQ}\wedge F^{Y}} + \cancel{D_3\ a\ F^{Y}\wedge F^{Y}}$$

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

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

Chern-Simons terms

We need non-invariant terms:

the variation

the variation

$$\mathcal{L}_{CS} = \Big[D_4 \; Y \wedge \cancel{A_{PQ}} \wedge F_{PQ} - D_5 \; A_{PQ} \wedge \cancel{Y} \wedge F_Y \Big]$$

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

$$\delta\mathcal{L}_{1-loop} = \epsilon \Big[\cancel{\frac{c_3}{3} F^{PQ}} \wedge F^{PQ} + \cancel{c_2 F^{PQ}} \wedge F^{Y} + \cancel{c_1 F^{Y}} \wedge F^{Y} + \cancel{\xi Tr[G} \wedge G] \Big]$$
$$+ \zeta \Big[c_2 F^{PQ} \wedge \cancel{F^{PQ}} + c_1 F^{PQ} \wedge \cancel{F^{Y}} \Big]$$

To cancel the anomalies we obtain:

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

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

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The General Case

Consider the general Lagrangian:

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

$$-\frac{1}{2}\sum_I(\partial_\mu a^I + \sum_i M_i^I A_\mu^i)^2$$

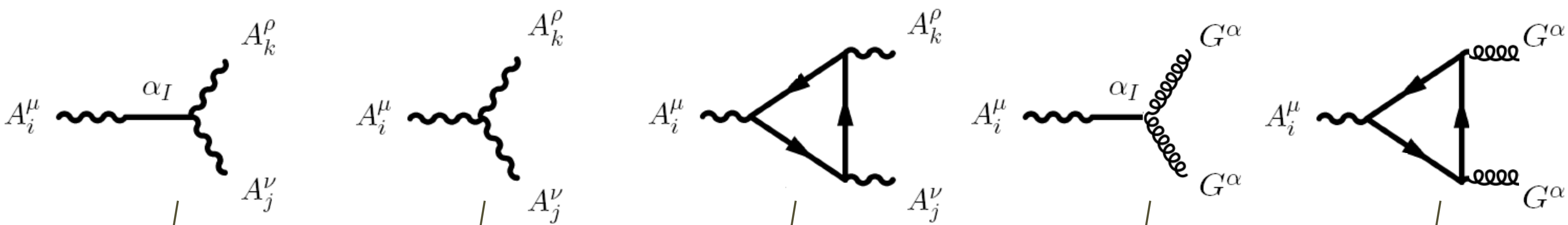
$$+\sum_{I,j,k} C_{Ijk}a^I F^j \wedge F^k + \sum_{I,a} D_{ia}a^I\ Tr[G^a \wedge G^a]$$

$$+\sum_{i,j,k} E_{ijk}\, A^i \wedge A^j \wedge F^k$$

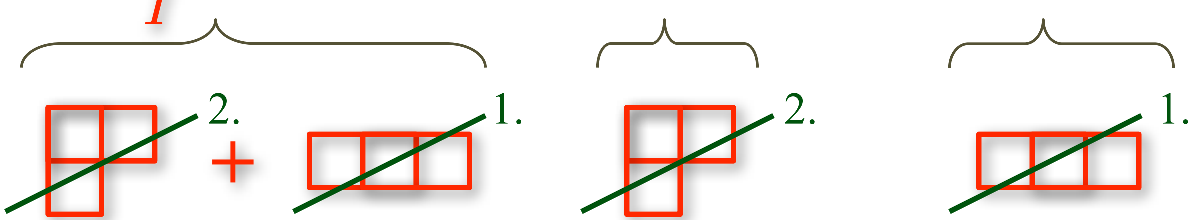
It is easy to show that: $E \sim \ydiagram{2,1}$

General Anomaly Cancellation

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:



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



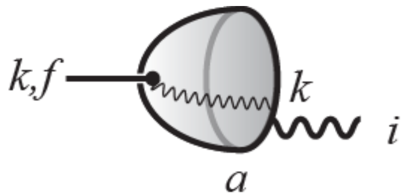
Special Cases: 1. No fermions.

2. Only one anomalous U(1).

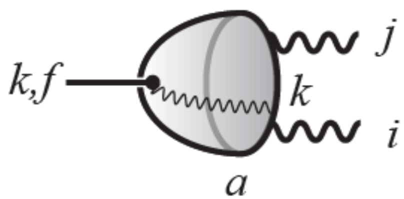
Andrianapoli Ferrara Lledo

Ibanez Rabadan Uranga Marchesano
Antoniadis Kiritsis Rizos etc

String Computation of GCS



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



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

The GCS-terms are:

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

which in general are different from zero.

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Example of GCS in Z6

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

- There are: $\left\{ \begin{array}{l} \text{2 non-anomalous} \\ \\ \text{4 anomalous} \end{array} \right. \rightarrow \left\{ \begin{array}{l} \text{1 massless} \\ \\ \text{5 massive} \end{array} \right.$

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- Non-zero GCS are needed: $E_{ijj} \sim \begin{pmatrix} 0 & 36 & -72 & 36 & 0 & -24 \\ -36 & 0 & 72 & 0 & -36 & 24 \\ 24 & -24 & 0 & 24 & -24 & 0 \\ 36 & 0 & -24 & 0 & 36 & -72 \\ 0 & -36 & 24 & -36 & 0 & 72 \\ 24 & -24 & 0 & 24 & -24 & 0 \end{pmatrix}$

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New couplings in D-brane models

- As it was mentioned before, all D-brane realizations of the Standard Model contain:
  - at least one massless U(1) (the Hypercharge)
  - various anomalous U(1)´s, which behave (almost) like Z´s.
- It becomes clear that Generalized Chern-Simons terms are needed to cancel all the anomalies.
- Such terms provide new couplings, that distinguish D-brane models from all the Z´-models studied in the past.

Z-Z´ Mixings

- Therefore, new anomaly-related couplings are present between the U(1)´s in the "Hypercharge"-basis.

- These couplings provide <u>very interesting decays</u> in the "photon"-basis.

- From Hypercharge to the photon-basis, we perform a rotation:

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

where the coefficients are:

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

CS Couplings and LHC

- Consider an anomaly canceling GCS-term like:

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

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

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

Coriano Irges Kiritsis

MSSM and anomalous U(1)'s

- In order to study the phenomenological implications of the anomalous U(1)'s and the anomaly related coupling, we will focus on an extension of the MSSM with:

  - an additional anomalous vector multiplet V' and

  - an axionic multiplet S .

- These superfields transform as:

$$V' \to V' + i(\Lambda - \Lambda^\dagger)$$
$$S \to S + 4\, i\, M\, \Lambda$$

under the additional U(1).

MSSM with one anomalous U(1)

- The MSSM particles are now charged under the additional vector multiplet:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	Q_Q
U_i^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	Q_{U^c}
D_i^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	Q_{D^c}
L_i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	Q_L
E_i^c	$\mathbf{1}$	$\mathbf{1}$	1	Q_{E^c}
H_u	$\mathbf{1}$	$\mathbf{2}$	$1/2$	Q_{H_u}
H_d	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	Q_{H_d}

- These charges are in principle independent.

MSSM with one anomalous U(1)

- Since we extend the MSSM, the usual Yukawa-terms,

$$\mathcal{L}_W = \left(y_u^{ij} Q_i U_j^c H_u - y_d^{ij} Q_i D_j^c H_d - y_e^{ij} L_i E_j^c H_d + \mu H_u H_d\right)_{\theta^2} + h.c.$$

and charge universality constrain these charges,

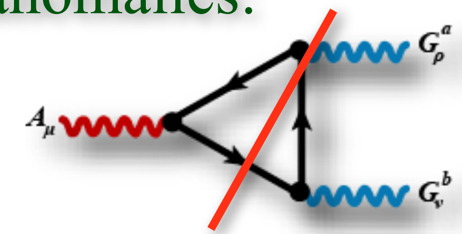
$$\begin{array}{rrcl} \rightarrow & Q_U & = & -Q_Q - Q_{H_u} \\ \rightarrow & Q_D & = & -Q_Q + Q_{H_u} \\ \rightarrow & Q_E & = & -Q_L + Q_{H_u} \\ \rightarrow & Q_{H_d} & = & -Q_{H_u} \end{array}$$

remaining with just three free parameters: $Q_Q \;, \quad Q_L \;, \quad Q_{H_u} \;.$

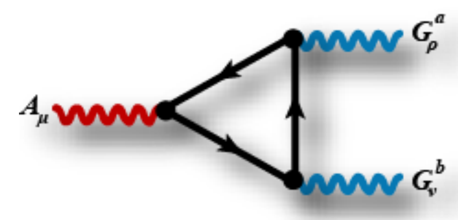
Possible Anomalies

- For the (quite) general charges, we might have the anomalies:

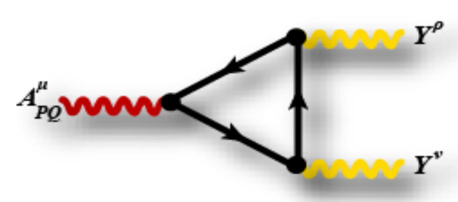
$Tr[QT^a_{(3)}T^b_{(3)}]$



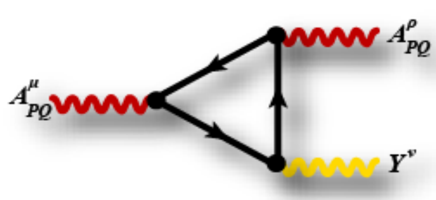
$Tr[QT^a_{(2)}T^b_{(2)}]$



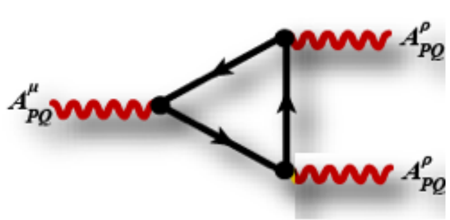
$Tr[QYY]$



$Tr[QQY]$



$Tr[QQQ]$



MSSM & U(1): Stückelberg Terms

- In order to cancel the anomalies, we have to add to the usual MSSM Lagrangian, the SUSY extension of the axionic (Stückelberg) terms:

$$\mathcal{L}_{axion} = \frac{1}{2}(\partial_\mu a + M A_\mu)^2 + \frac{\zeta}{M}\, a\, Tr[G \wedge G]$$

which become:

$$\mathcal{L}_{axion} = -\frac{1}{4}(S + \bar{S} - 2MV^{(0)})^2\Big|_{\theta^2\bar{\theta}^2}$$
$$-\frac{1}{2}\Big\{\Big[c^{(a)}\; S\; Tr[W^{(a)}W^{(a)}] + c^{(4)}\; S\; W^{(1)}W^{(0)}\Big]_{\theta^2} + h.c.\Big\}$$

- The M, $c^{(a)}$, $c^{(4)}$ are parameters and will be fixed by anomaly cancellation.

MSSM & U(1): GCS Terms

- The Generalized Chern-Simons terms:

$$\mathcal{L}_{CS} = \Big[D_4\, Y \wedge A_{PQ} \wedge F_{PQ} - D_5\, A_{PQ} \wedge Y \wedge F_Y \Big]$$

will be "supersymmetrized" to:

$$\begin{aligned}
\mathcal{L}_{GCS} = & -d_4 \Big[\Big(V^{(1)} D^\alpha V^{(0)} - V^{(0)} D^\alpha V^{(1)} \Big) W_\alpha^{(0)} + h.c. \Big]_{\theta^2 \bar{\theta}^2} \\
& + d_5 \Big[\Big(V^{(1)} D^\alpha V^{(0)} - V^{(0)} D^\alpha V^{(1)} \Big) W_\alpha^{(1)} + h.c. \Big]_{\theta^2 \bar{\theta}^2} \\
& + d_6 Tr \Big[\Big(V^{(2)} D^\alpha V^{(0)} - V^{(0)} D^\alpha V^{(2)} \Big) W_\alpha^{(2)} \\
& \qquad + \frac{1}{6} V^{(2)} D^\alpha V^{(0)} \bar{D}^2 \Big(\Big[D_\alpha V^{(2)}, V^{(2)} \Big] \Big) + h.c. \Big]_{\theta^2 \bar{\theta}^2}
\end{aligned}$$

- The $d_4,\ d_5,\ d_6$ are again parameters and will be fixed by anomaly cancellation.

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MSSM & U(1): Soft Breaking Terms

- For the soft-breaking terms, we can now include contributions from:
  - the gaugino (prime) λ'
  - the axion $\cancel{a}$
  - the axino ψ_S
- However, the axion do not contribute due to its particular transformation and the only new soft-terms are:

$$\mathcal{L}^{new}_{soft} = -\frac{1}{2}(M'\lambda'\lambda' + h.c.) - \frac{1}{2}(M_S\psi_S\psi_S + h.c.)$$

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MSSM & U(1): New Terms

- Kinetic Mixing (from Stückelberg terms)

$$\frac{1}{4}W^{(0)}W^{(0)} + \frac{1}{4}W^{(1)}W^{(1)} - 2b_2^{(4)}g_0 g_1 \langle\alpha\rangle W^{(1)}W^{(0)}\Big|_{\theta^2}$$

However, since $b_2^{(4)} \sim 1/b_3 \sim 1/M_{V^{(0)}}$ and $M_{V^{(0)}} \sim 1\ TeV$, such mixing will be ignored for our purposes.

- In addition, we have new D- & F- terms (from Stückelberg) which contribute the the superpotential adding
  - new interactions and
  - modifying the masses of the particles.

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MSSM & U(1): Photon

- After diagonalizations of the U(1) factors we obtain:

$$A_\mu = \frac{g_2 B_\mu + g_1 V^{(2)}_{3\mu}}{\sqrt{g_1^2 + g_2^2}}$$

$$Z_0^\mu = \frac{g_2 A^{3\mu} - g_1 B^\mu}{\sqrt{g_1^2 + g_2^2}} + g_0 Q_{H_u} \frac{\sqrt{g_1^2 + g_2^2} v^2}{2 M^2_{V^{(0)}}} C^\mu + \mathcal{O}[g_0^3, M^{-3}_{V^{(0)}}]$$

$$Z'^\mu = C^\mu + \frac{g_0 Q_{H_u} v^2}{2 M^2_{V^{(0)}}} \left(g_1 B^\mu - g_2 A^{3\mu}\right) + \mathcal{O}[g_0^3, M^{-3}_{V^{(0)}}]$$

with corresponding masses:

$$M_\gamma^2 = 0$$

$$M^2_{Z_0} = \frac{1}{4}\left(g_1^2 + g_2^2\right) v^2 - (Q_{H_u})^2 \frac{\left(g_1^2 + g_2^2\right) g_0^2 v^4}{4 M^2_{V^{(0)}}} + \mathcal{O}[g_0^3, M^{-3}_{V^{(0)}}]$$

$$M^2_{Z'} = M^2_{V^{(0)}} + g_0^2 \left[(Q_{H_u})^2 \left(1 + \frac{g_1^2 v^2 + g_2^2 v^2}{4 M^2_{V^{(0)}}}\right) - \frac{\langle\alpha\rangle g_1^3 \mathcal{A}^{(4)}}{64 \pi^2 M_{V^{(0)}}}\right] v^2 + \mathcal{O}[g_0^3, M^{-3}_{V^{(0)}}]$$

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Ward Identities

- Our model still contains various unknown parameters, related to the Stückelberg and the GCS terms.

- In order to fix them, we use the Ward-Identities, where in the broken phase look like:

$-ik^{\mu} \Big(V^{\mu}(k)$  1PI $\Big) + m_V \Big(G_V(k)$  1PI $\Big) = 0$

where: - V^{μ} the massive gauge boson,

- G_V the related "would be" Goldston Boson

and m_V the related mass coming from the coupling: $m_V V^{\mu} \partial_{\mu} G_V$.

Decays for different values

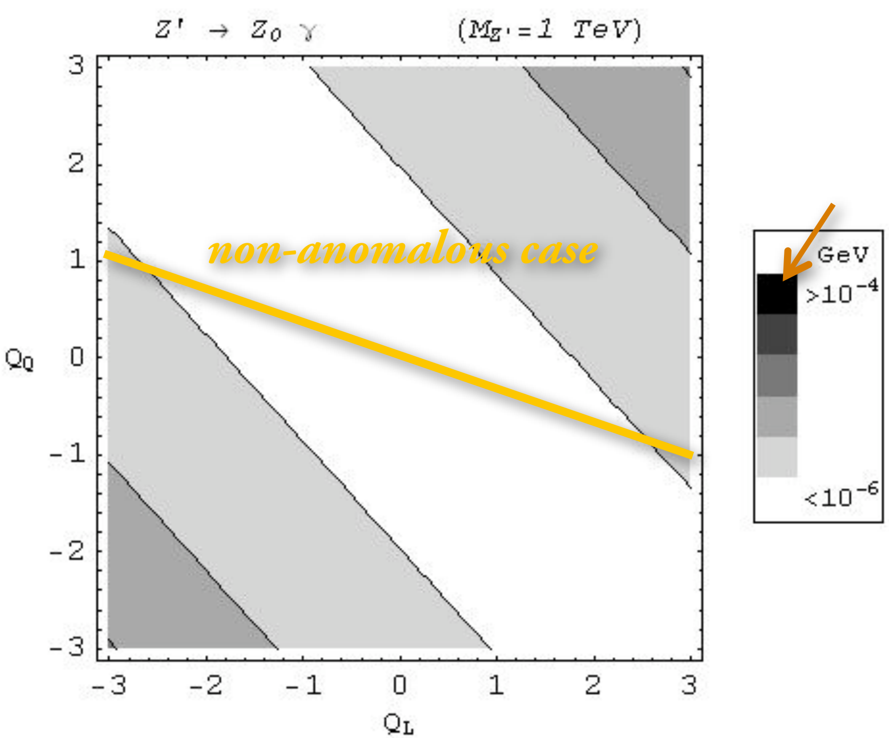
- After fixing the couplings of the Stückelberg and the GCS terms, we evaluated various processes for the only free parameters:
  - Various $M_{Z'}$.
  - Various charges Q_Q , Q_L , Q_{H_u} .
- In particular, we focus on the decays:

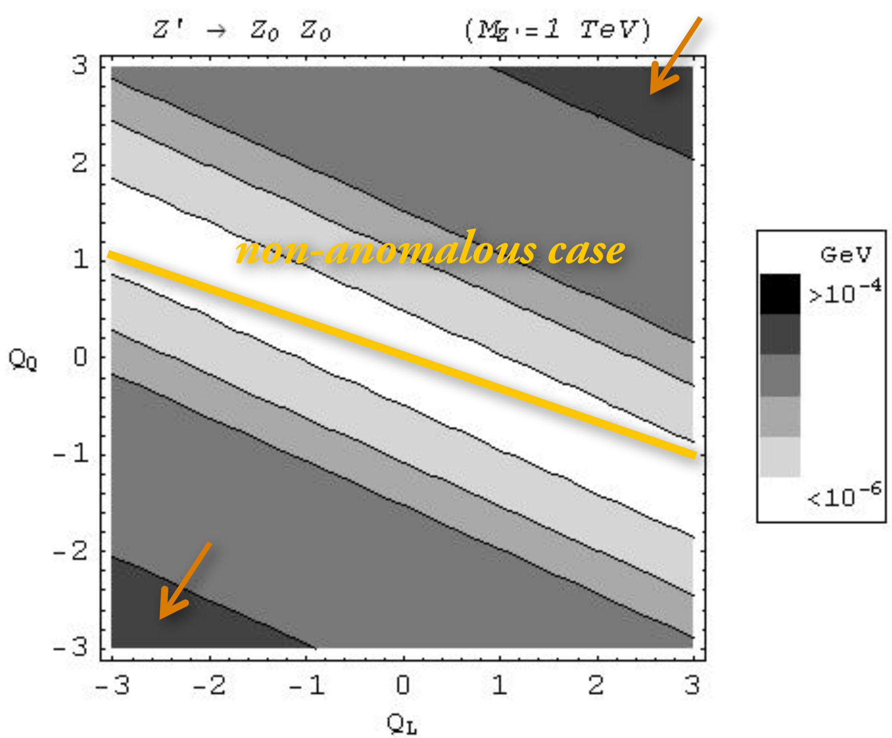
$$Z' \to Z_0\,\gamma \qquad\qquad Z' \to Z_0\,Z_0$$

- Fixing for simplicity: $Q_{H_u} = 0$.

$Z' \to Z_0\,\gamma \quad \& \quad Z' \to Z_0\,Z_0$

- Decay rates: for $M_{Z'} = 1\ TeV$





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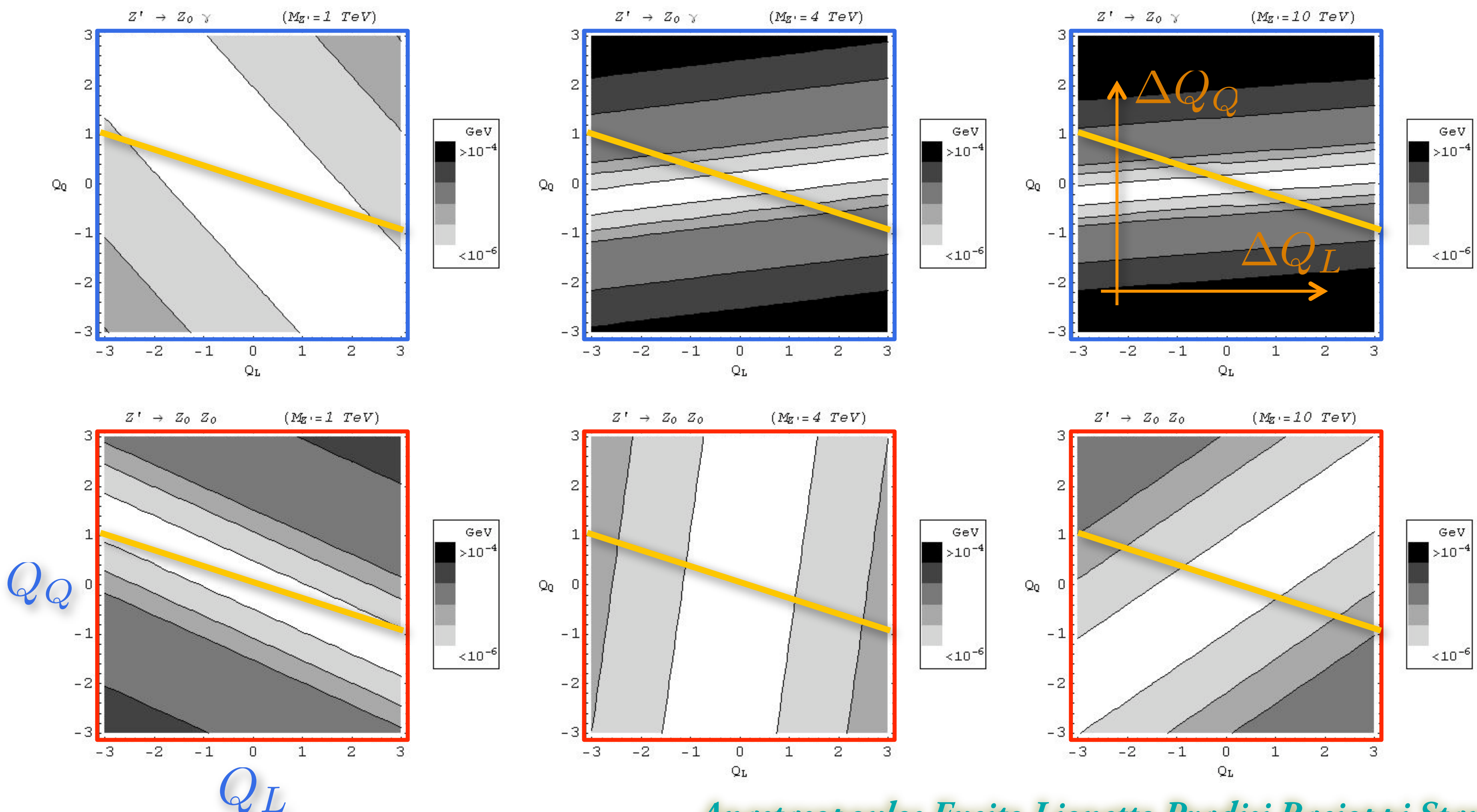
Decay rates for $Z' \to Z_0\,\gamma$ & $Z' \to Z_0\,Z_0$.

$M_{Z'} = 1\ TeV$ $M_{Z'} = 4\ TeV$ $M_{Z'} = 10\ TeV$



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Z′ at LHC

- Even though the detection of the Z′ is expected in Drell-Yan processes, its anomalous or non-anomalous nature could be tested by decays of the form: $Z' \to Z\gamma, \;\; Z' \to ZZ.$
- These decays will lead to four lepton events - a very clean signal that might be visible at LHC.
- A detailed phenomenological analysis with Monte Carlo generators is required for searches at the LHC where a very accurate determination of the QCD and electroweak backgrounds will be considered.

Conclusions

- Anomalous U(1)´s are a generic prediction of all D-brane Standard Models.
- These U(1)´s are massive and if the string scale is low (few TeV region) such gauge bosons become the tell-tales signals of these models.
- Anomaly related Chern Simons-like couplings produce new couplings that distinguish such models from other Z´-models studied in the past.
- Such signals may be visible at LHC.