Liverpool, March 2008

Anomalous U(1)s and LHC

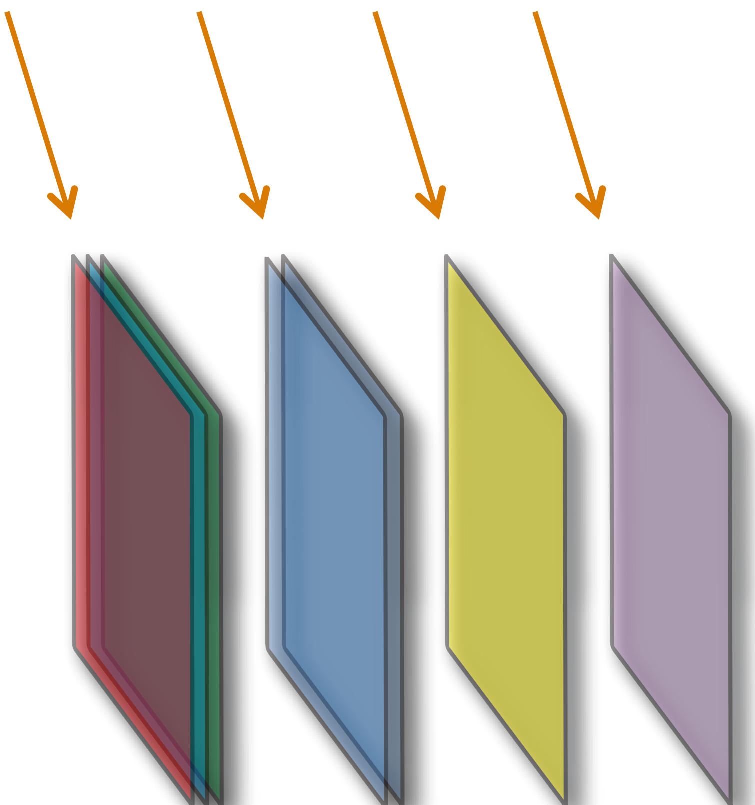
Pascal Anastasopoulos
INFN, Roma “Tor Vergata”

Plan of the talk

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

Typical D-brane Standard Models

- Typically, the Standard Model is located on some stacks of branes (intersecting or not):



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

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

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

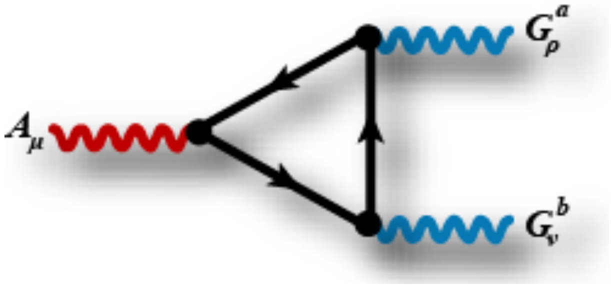
- Up to today, there is no model that successfully describes <u>all</u> the characteristics of the Standard Model. We are working on this…
- However, if there is a D-brane model that might describes the SM, then it predicts many U(1)´s (as many as the number of the stack of D-branes that participate).
- From these U(1)´s:
  - One is the Hypercharge (massless and anomaly-free)
  - The rest are superficially anomalous (?!)

Anomalous U(1)´s

Consider a chiral gauge theory:

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

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

To cancel the anomaly we add an axion:

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

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

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

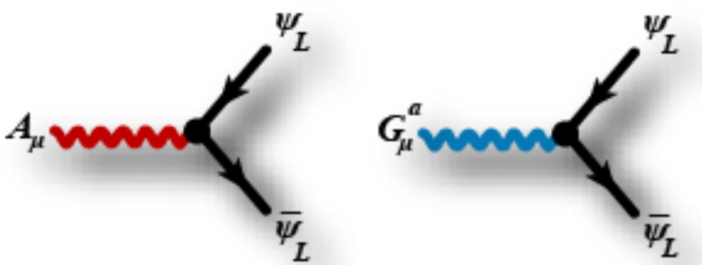
and the anomaly is cancelled.

Green-Schwarz
Sagnotti
Ibanez Rabadan Uranga

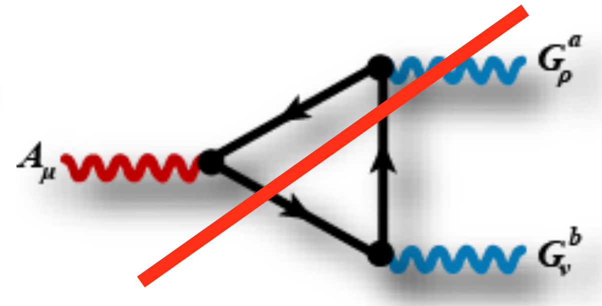
Anomalous U(1)′s (in diagrams)

Consider a chiral gauge theory:

$$\mathcal{L} = -\frac{1}{4g_A^2}F^2 - \frac{1}{4g_G^2}Tr[G^2] + \bar{\psi}_L\gamma^\mu(\partial_\mu + ig_A A_\mu + ig_G T^a G^a_\mu)\psi_L$$

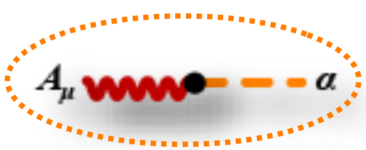


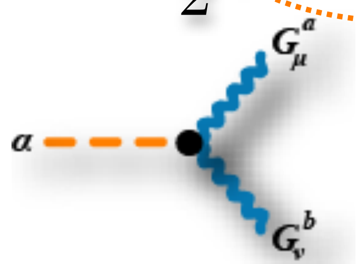
$$\zeta = Tr[QT^aT^a] \neq 0$$

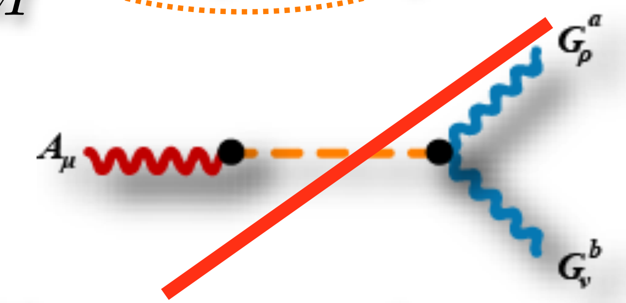


The axionic Lagrangian:

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







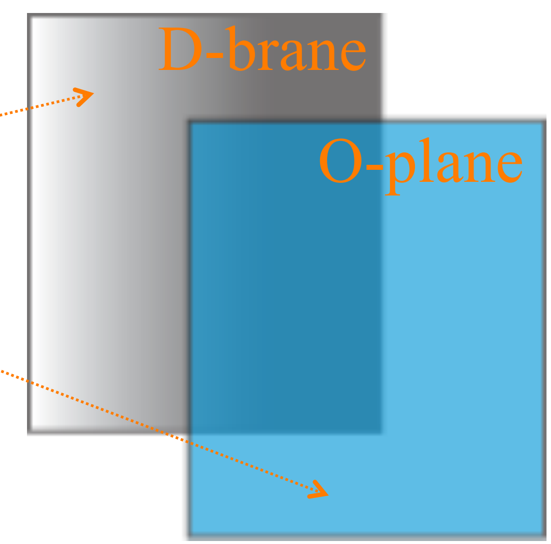
The anomaly is cancelled. The anomalous U(1)′ becomes massive.

Green-Schwarz
Sagnotti

Anomalous U(1)´s masses

- 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-pane where the axion is localized:

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



Antoniadis Kiritsis Rizos

Hypercharge & anomalous U(1)´s

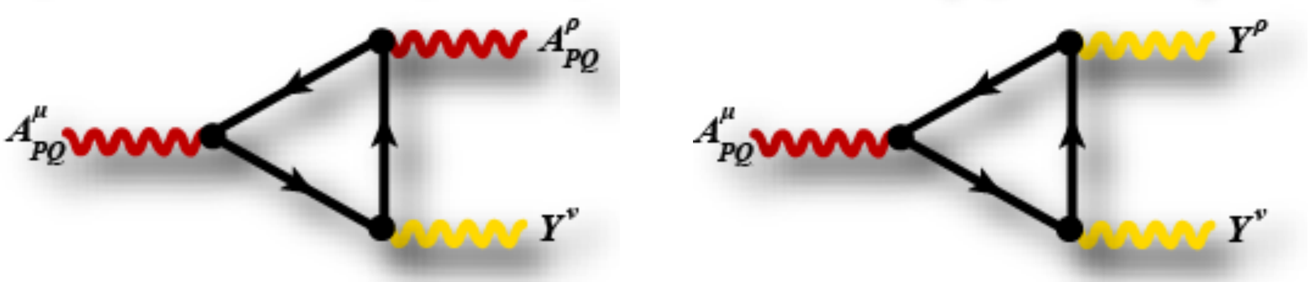
For the Hypercharge Y^μ, we have:

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

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

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

The need of Chern-Simons terms

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

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

To cancel the anomalies we add axions as before:

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

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

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

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

Chern-Simons terms

We need non-invariant terms:

the variation the variation

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

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

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

To cancel the anomalies we obtain:

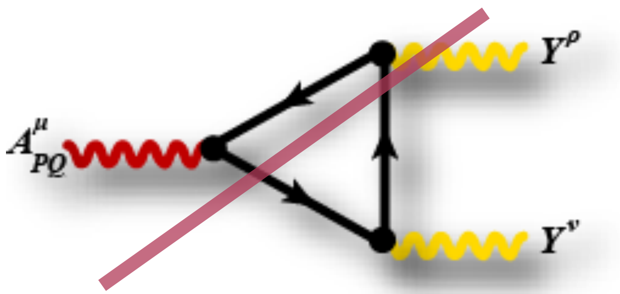
$$D_0 = \xi, \ D_1 = \frac{c_3}{3}, \ D_2 = 2c_2, \ D_3 = 2c_1, \ D_4 = c_2, \ D_5 = c_1$$

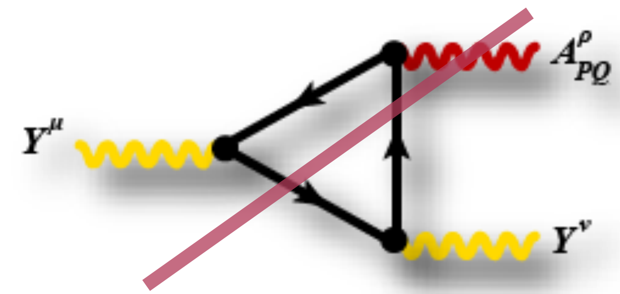
The anomalies fix the coefficients of the GCS-terms in the effective action.

Anastasopoulos Bianchi Dudas Kiritsis

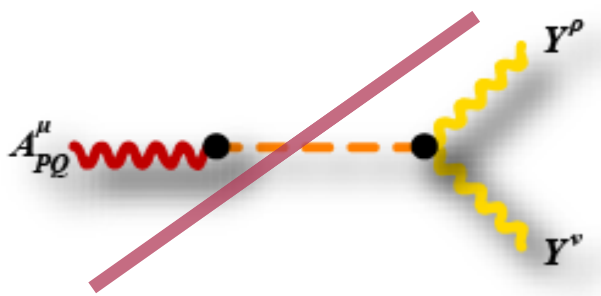
Chern-Simons terms (in diagrams)

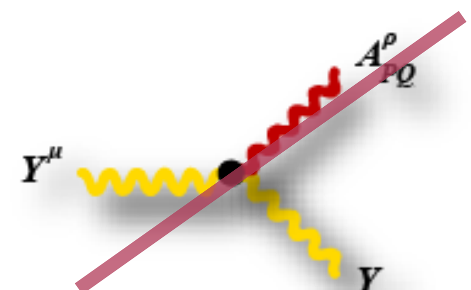
If $Tr[QYY] \neq 0$, there are anomalies due to the diagram:





Now, the axionic terms are not enough to cancel the anomalies:





We need a GCS-term: $\epsilon_{\mu\nu\rho\sigma} A^\mu_{PQ} Y^\nu \partial^\rho Y^\sigma$

Anastasopoulos Bianchi Dudas Kiritsis

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.

CS Couplings and LHC

- Consider the various anomaly canceling GCS-terms :

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

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

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

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}

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

MSSM & U(1): Stückelberg and GCS Terms

- Apart from the usual MSSM Lagrangian, we have now the Stückelberg terms:

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

- And the Generalized Chern-Simons terms:

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

MSSM & U(1): Soft Breaking Terms

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

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

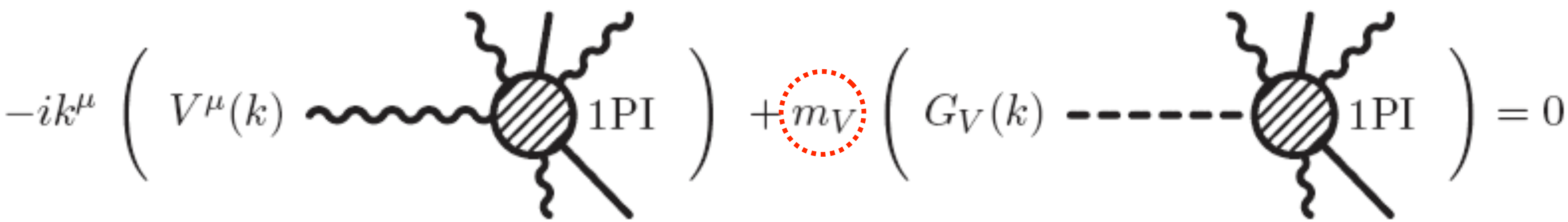
MSSM & U(1): New Terms

- New features:
  - Kinetic Mixing (from Stückelberg)
  - New D- & F- terms (from Stückelberg)
  - New soft-breaking terms
- After diagonalizations we obtain:
  - A massless gauge boson (photon)
  - New couplings
  - New contributions to the masses.

Anastasopoulos Fucito Lionetto Pradisi Racioppi Stanev

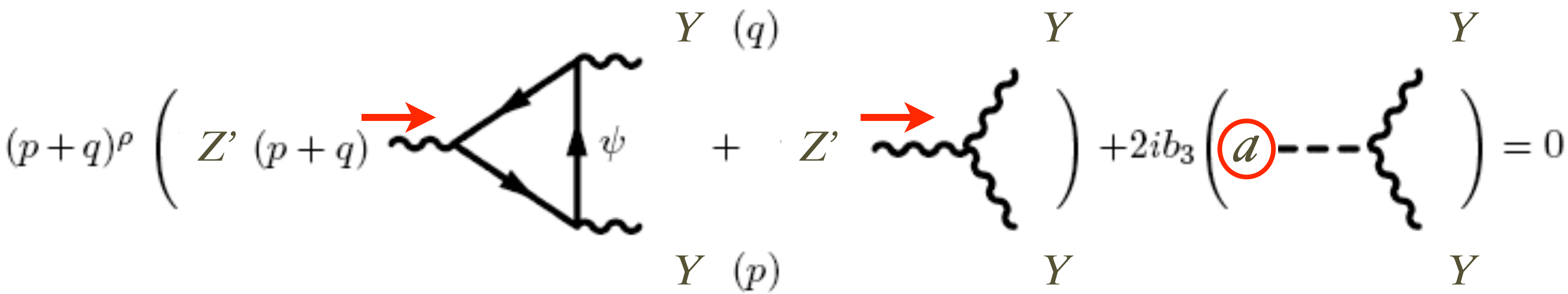
Ward Identities

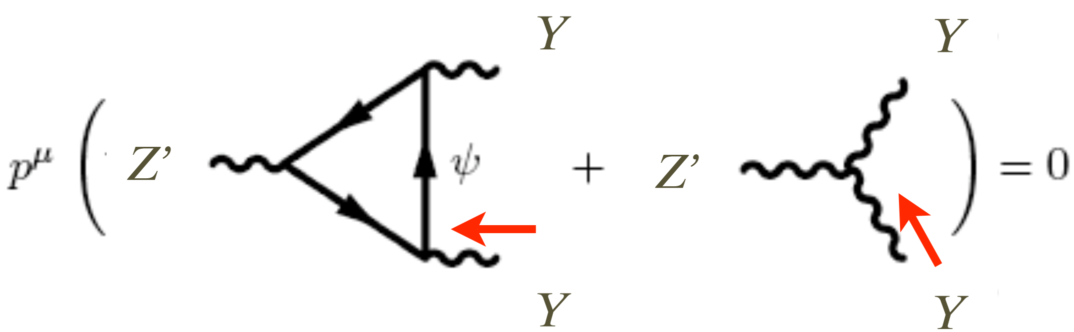
- In order to fix the unknown parameters of our model, we use the Ward-Identities:

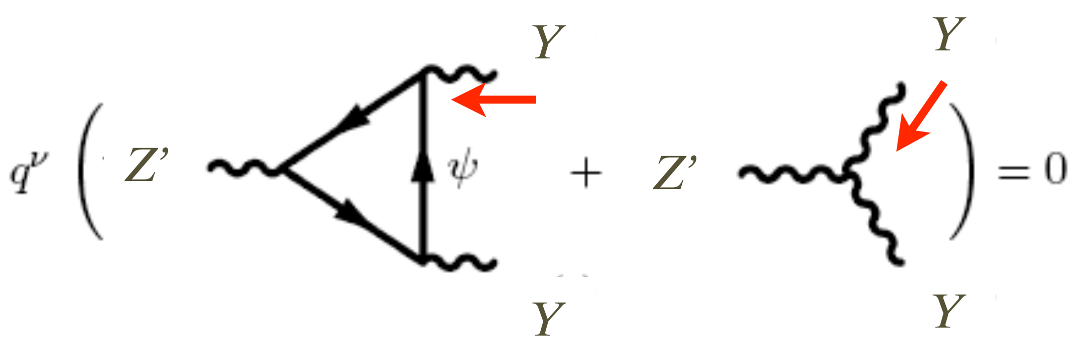


where m_V is coming from the coupling: $m_V V^{\mu}\partial_{\mu}G_V$.

Ward Identities in the unbroken phase

- 

- 

- 

Anastasopoulos Fucito Lionetto Pradisi Racioppi Stanev

Decays for different values

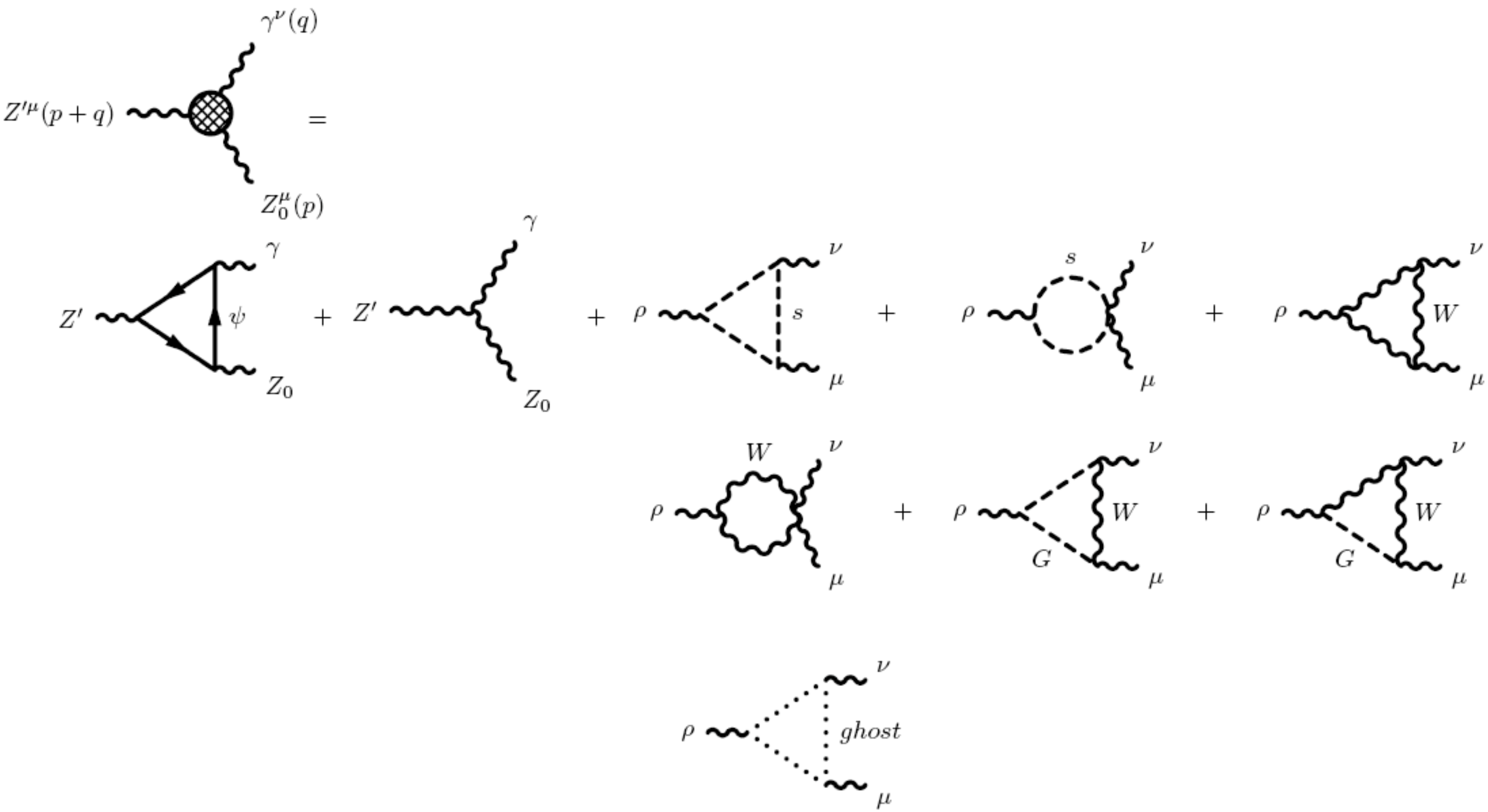
- After fixing the couplings of the Stückelberg and the GCS terms, we evaluated various processes for:
  - Various $M_{Z'}$.
  - Various charges Q_Q , Q_L , Q_{H_u} .
- In particular, we focus on the decays:

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

fixing however for simplicity: $Q_{H_u} = 0$.

Anastasopoulos Fucito Lionetto Pradisi Racioppi Stanev

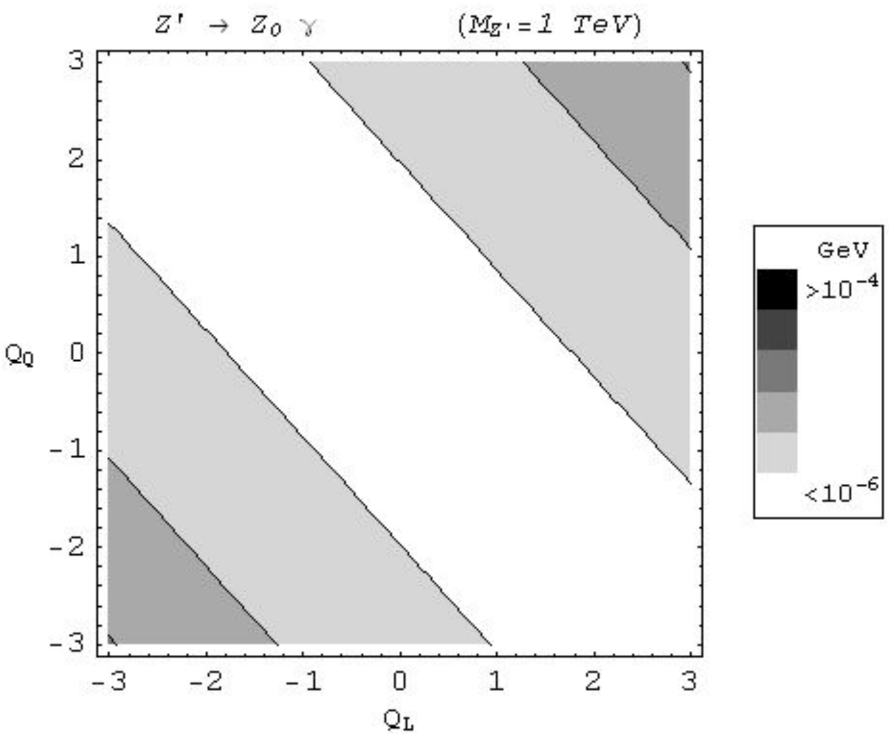
The decay $Z' \to Z_0\,\gamma$.

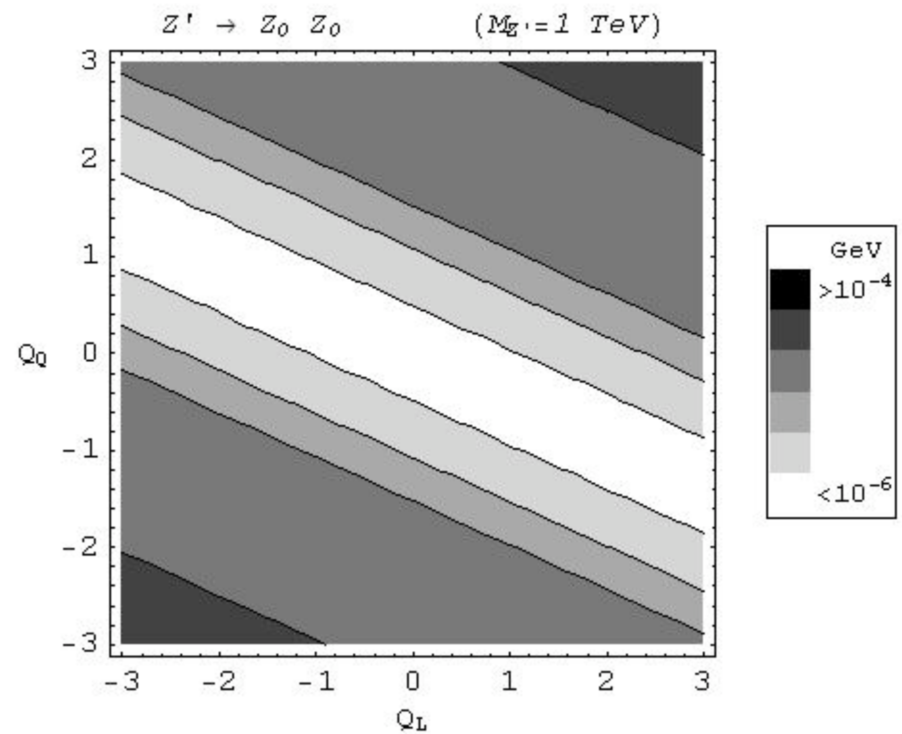


Anastasopoulos Fucito Lionetto Pradisi Racioppi Stanev

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

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

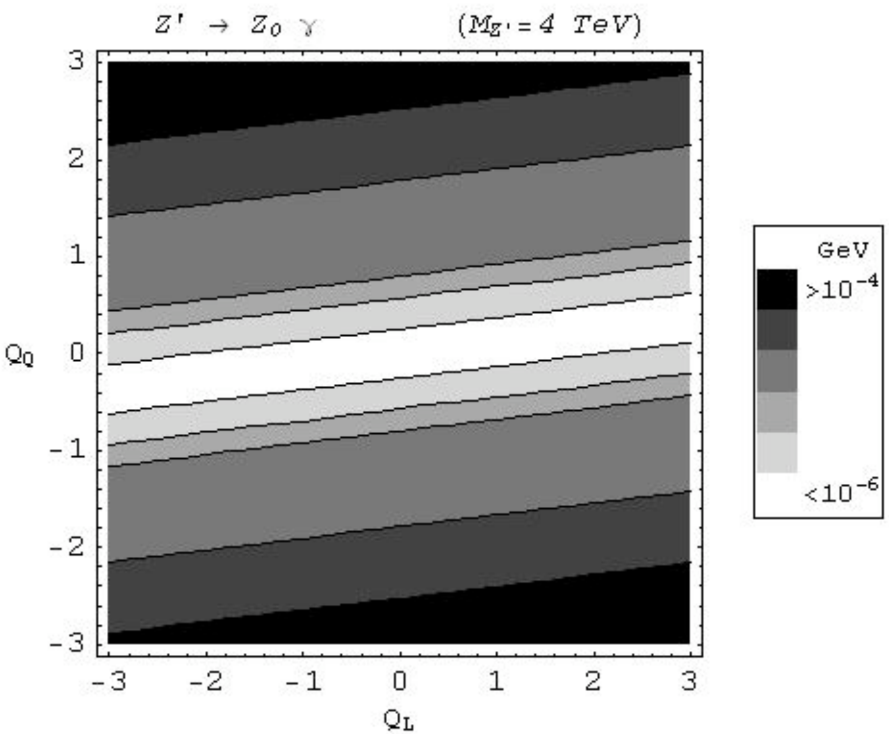


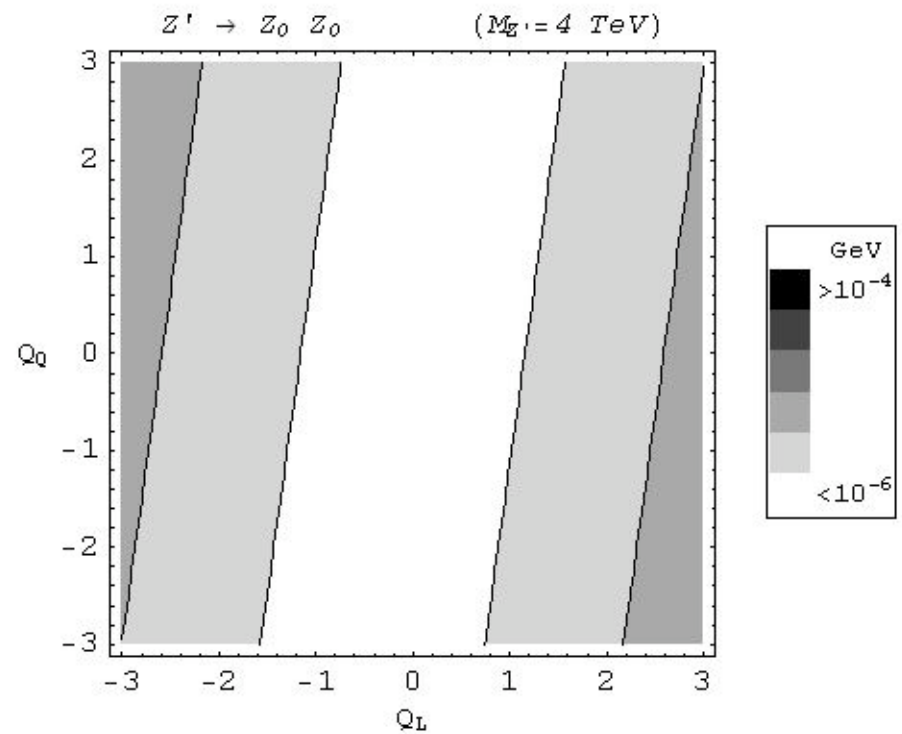


Anastasopoulos Fucito Lionetto Pradisi Racioppi Stanev

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

- Results: for $M_{Z'} = 4\, TeV$

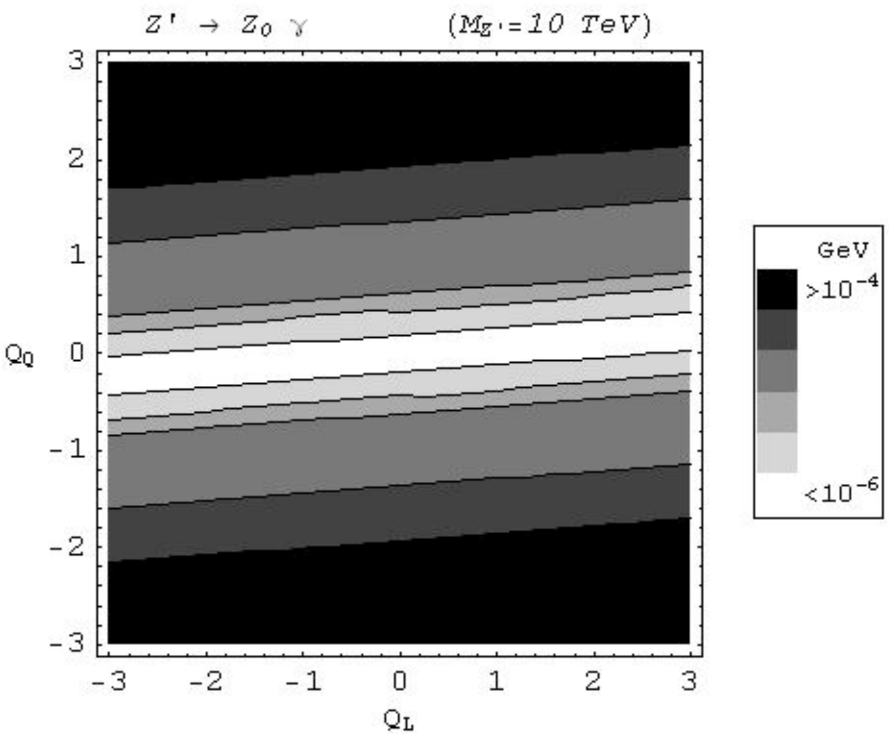


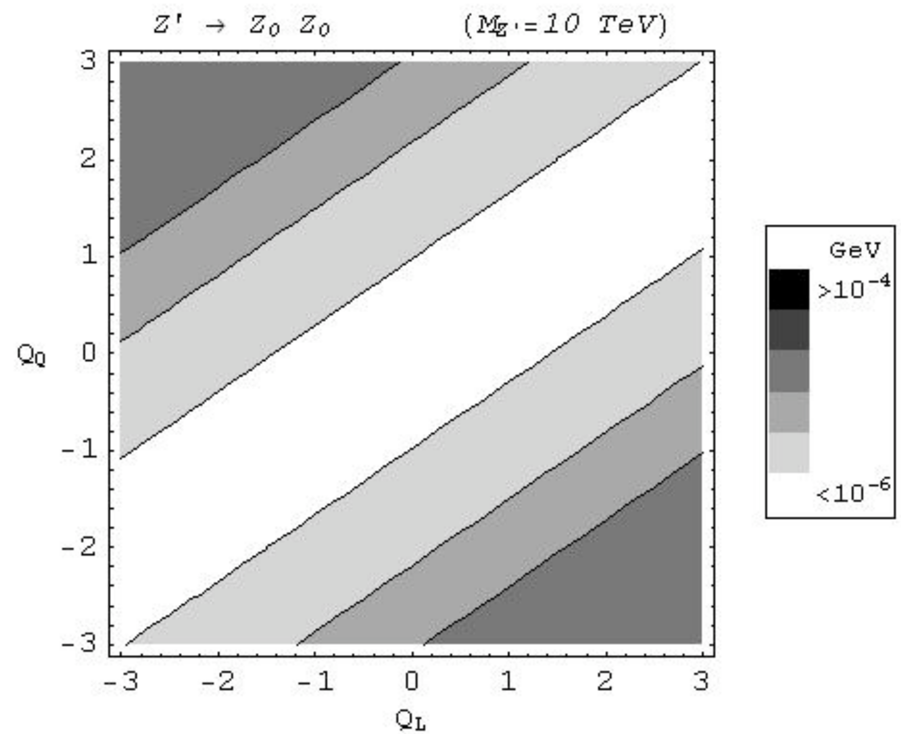


Anastasopoulos Fucito Lionetto Pradisi Racioppi Stanev

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

- Results: for $M_{Z'} = 10\ TeV$





Anastasopoulos Fucito Lionetto Pradisi Racioppi Stanev

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 signals that distinguish such models from other Z´-models studied in the past.
- Such signals may be visible at LHC.