This research has been co-financed by the European Union (European Social Fund, ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF), under the grants schemes "Funding of proposals that have received a positive evaluation in the 3rd and 4th Call of ERC Grant Schemes" and the program "Thales"

European Union
European Social Fund

OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS, CULTURE & SPORTS
MANAGING AUTHORITY

NSRF
2007-2013
programme for development
EUROPEAN SOCIAL FUND

Co-financed by Greece and the European Union

10th Patras Workshop on Axions WIMPs and WISPs
CERN, 2 July 2014

(Anomalous) U(1)s from string theory

Elias Kiritsis

CCTP University of Crete CERN APC, Paris

Introduction

• Quantum Field Theory is a framework (and not a "theory") that is underlying our theories of the fundamental interactions.

• Many of us think that String Theory is also a framework that unifies gravity with gauge interactions.

• We have good reasons to believe today that string theory is another face of Quantum Field Theory (via the AdS/CFT correspondence) or vice versa.

• It seems to have a large number of vacua (landscape).

• If these vacua are connected by physical processes, then one has to take them seriously.

• If not, then we are in the same ball-park as in QFT.

• We do not know today which of the previous statements is true.

Particle physics and string theory

• The effort of building theories (vacua?) that look like the SM in string theory is at least 30 year old.

• There has been partial success in this, at least in building supersymmetric vacua.

• Doing this in string theory is orders of magnitude harder than QFT because:

♠You cannot sweep the cosmological constant problem under the rug.

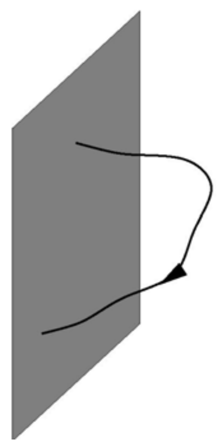
♠Because what we observe at low energy (particles, masses and interactions) is not what you put in to construct the theory (geometry, CFT, fluxes, branes)

• Despite the above, from this multi-decade effort we have learned several general lessons about particle interactions beyond the standard model and how they intertwine with gravity and other fundamental issues (black holes etc).

Particle physics and string theory, II

• There is a class of vacua which are simpler to think about, as the particle and gauge group content is "modular": those containing D-branes.

• The main ingredient: A D_p-brane is roughly a p-dimensional submanifold embedded in the 9 spatial dimensions of space-time.

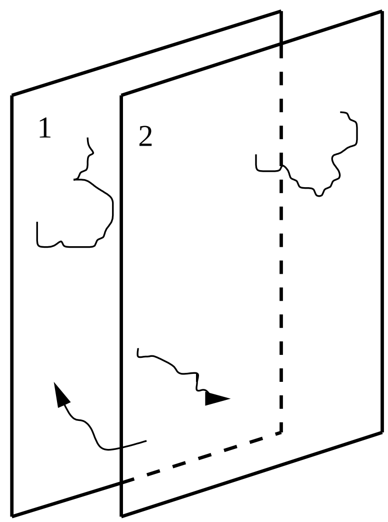


• The difference from a simple wall is that they can fluctuate via open strings whose endpoints are attached to the branes.

• A generic massless fluctuation is a gauge boson living on the world volume. $\to$ U(1)

Non-abelian gauge symmetry

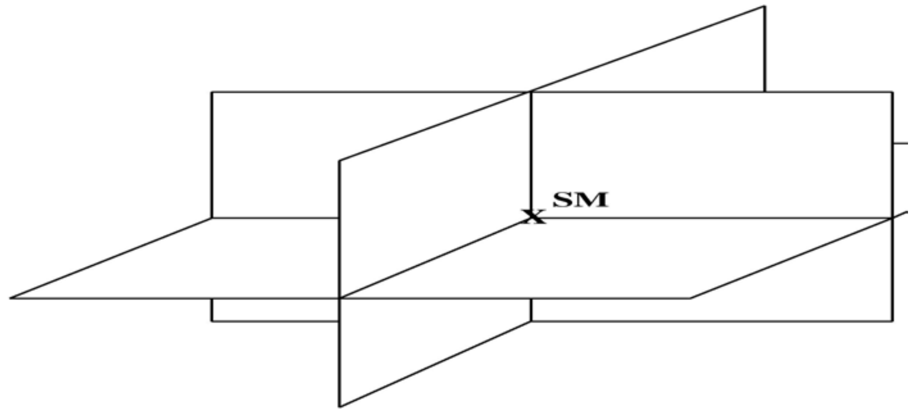
D-branes have a remarkable property that leads to a "geometrization" of gauge dynamics which eventually led to AdS/CFT and bulk-boundary correspondence



Two parallel coincident D-branes have four distinct open string fluctuations (11, 12, 21, 22). Each one provides a massless gauge boson. The gauge group turns out to be U(2) !!!

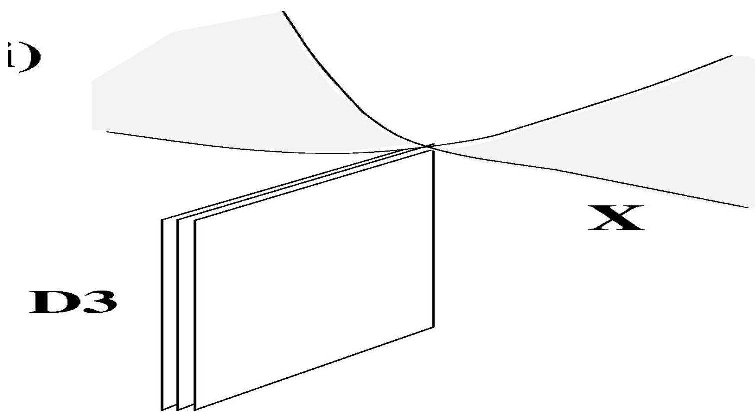
- ALL UNITARY GROUPS are U(N). The overall U(1) is generically anomalous!

There are more complicated configurations , like branes intersecting at angles. They are equivalent to branes with background internal magnetic fields.



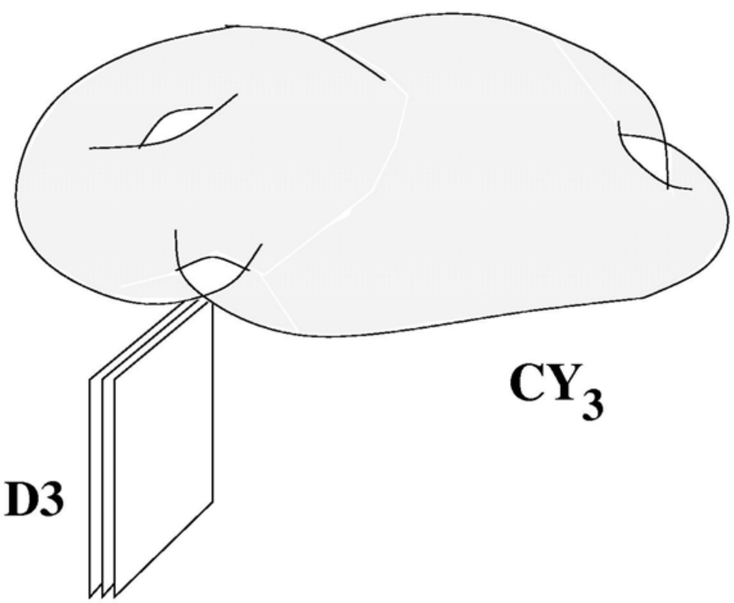
• Such magnetic fields reduce the amount of supersymmetry and generate chirality

Chirality can also be obtained when D-branes are transverse to appropriate conical singularities.



The mathematical formalism of describing the dynamics of D-branes in string theory is known as BCFT.

Orientifolds



• The closed string theory is compactified on a 6d compact manifold × 4d Minkowski space-time.

• There are several D-branes that stretch along Minkowski space, and if they have extra dimensions they wrap parts of the compact 6d manifold. They form the "matter" gauge group.

♣The string scale M_s is no longer required to be near the Planck scale.

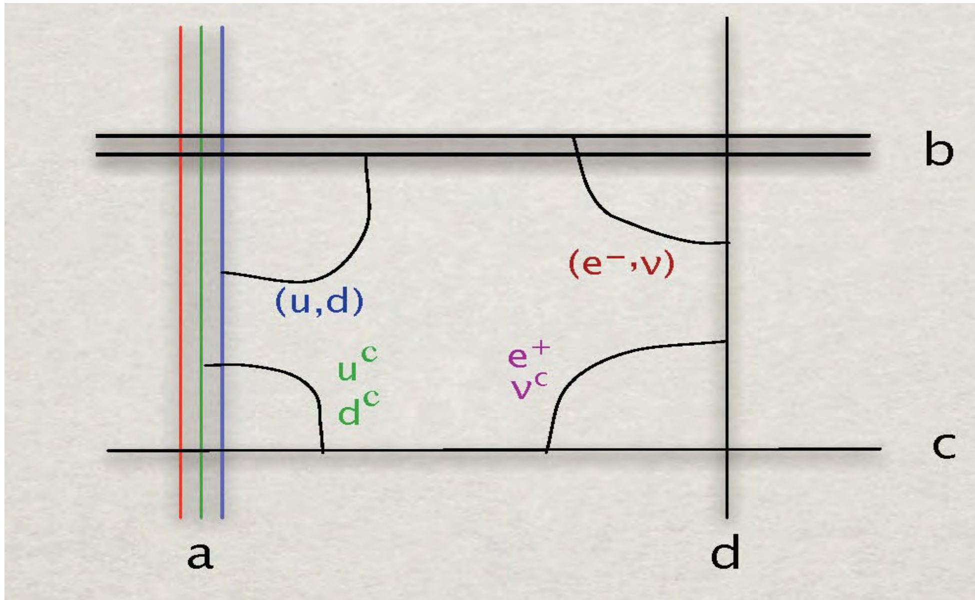
♠Susy may break at M_s

• One can apply the bottom-up approach: construct local D-brane brane configurations that reproduce SM physics, without worrying about global stability.

Antoniadis+Kiritsis+Tomaras '00
Aldazabal+Ibanez+Quevedo+Uranga '00

Embedding the SM in orientifolds

Fix the configuration: U(3)× U(2)× U(1)× U(1)'



Search for: Chiral $SU(3) \times SU(2) \times U(1)$ spectrum:

Ibañez+Marchesano+Rabadan, '01
Dijkstra+Huiszoon+Schellekens, '06

$$3(u,d)_L + 3u_L^c + 3d_L^c + 3(e^-,\nu)_L + 3e_L^+$$

$$\text{Massless} \quad Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d$$

N=1 SUSY,

The hypercharge embedding

It has been realized early-on that the hypercharge embedding in orientifold models has several distinct possibilities that affect crucially the physics.

Antoniadis+Kiritsis+Tomaras, '00

$$U(3)_a \times \left\{ \begin{matrix} U(2) \\ SU(2) \end{matrix} \right\}_b \times G_c \times G_d$$

$$Y = \alpha Q_a + \beta Q_b + \gamma Q_c + \delta Q_d + W_c + W_d$$

$Q_i \to$ brane charges (unitary branes)

$W_i \to$ traceless (non-abelian) generators.

- All hypercharge embeddings have been classified.!

Antoniadis+Kiritsis+Tomaras, '00, Antoniadis+Dimopoulos, '04
Anroniadis+Kiritsis+Rizos+Tomaras, '02
Anastasopoulos+Dijkstra+Kiritsis+Schellekens, '06

Generic characteristics of Orientifold Vacua

- Unless the string scale is in the Multi-TeV range, they have few generic observable consequences. We focus from now on on low M_s.

- The have ALWAYS at least one (and typically more) U(1)'s that are beyond the SM.

Antoniadis+Kiritsis+Rizos+Tomaras '02

- The SM Higgs is ALWAYS charged under at least one of the extra U(1)'s

- Some but not all of the SM fermions can be charged under these additional U(1)'s

- There are GENERIC hidden sectors associated with brane stacks located in nearby regions of the compactification manifold.

- The extra U(1)' are generically anomalous, and therefore massive in string theory. They have axionic couplings that are central to our discussion.

- The associated global symmetries are always broken by instanton effects.

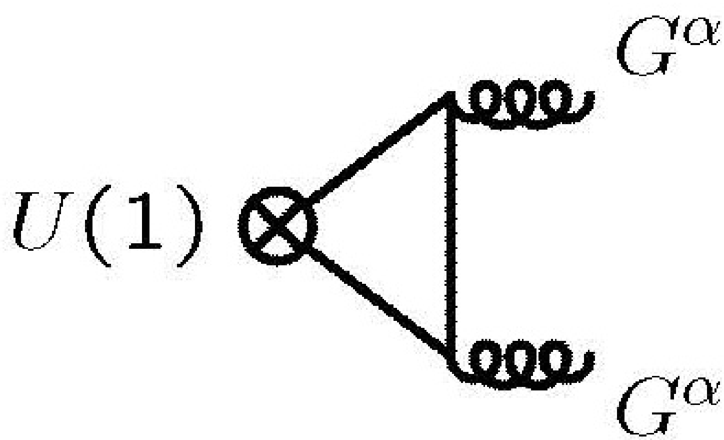
- They always include the baryon number symmetry that is gauged.

Anomalies and anomalous U(1)s in string theory

- The simplest example in 4d: A U(1) gauge symmetry that has a mixed triangle anomaly with a non-abelian group.

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

- The one-loop triangle diagram is non-zero



• It induces a non-invariance to U(1) gauge transformations

$$A_\mu \to A_\mu + \partial_\mu \epsilon \quad , \quad \delta L_{1-\text{loop}} = \epsilon\ \zeta\ Tr[G \wedge G]$$

• This is cancelled ALWAYS by a coupling to an axion field

$$\mathcal{L}_{\text{class}} \sim -\frac{1}{4g^2} F_{\mu\nu}^2 + \frac{1}{2}(\partial_\mu a + M\ A_\mu)^2 + \frac{\zeta}{M}\ a\ Tr[G \wedge G]$$

• The anomaly is cancelled because the axion now transforms as

$$a \to a - M\epsilon \quad , \quad \mathcal{L}_{\text{class}} \to \mathcal{L}_{\text{class}} - \zeta\ \epsilon\ Tr[G \wedge G]$$

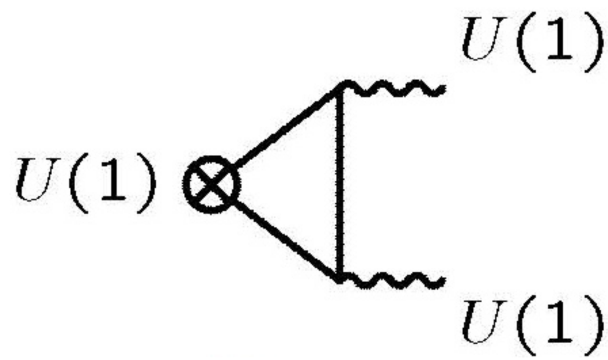
• The anomalous gauge field is massive for all of this to work.

• Even non-anomalous U(1)s can have masses and couplings to axions as above! The reason is that they may have 6d anomalies (not visible in 4 dimensions).

Antoniadis+Kiritsis+Rizos, '01

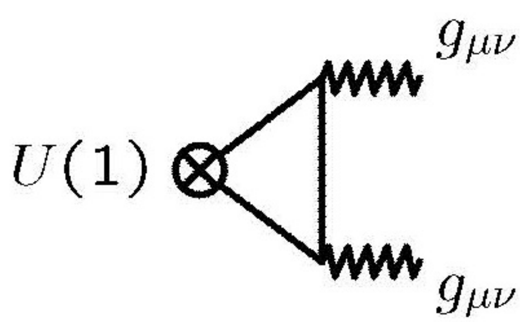
Anastasopoulos, '03

♣ There may also be $U(1)^3$ anomalies associated to $\tilde{\zeta} = Tr[Q^3] \neq 0$



♠It is cancelled by an extra term $\delta L = \frac{\tilde{\zeta}}{M}\ a\ F \wedge F$

♠ The mixed gauge-gravitational anomaly associated to $\hat{\zeta} = Tr[Q] \neq 0$ is coming from the diagram



• It is cancelled by the extra term $\delta L = \frac{\hat{\zeta}}{M}\ a\ R \wedge R$

Anomalous U(1) masses

♡ The Stückelberg term in the action mixes the U(1) gauge boson and the axion

$$\frac{1}{4g^2}F^2 + \frac{1}{2}(\partial_\mu a + M\ A_\mu)^2$$

• It gives mass to the anomalous gauge-boson and breaks the U(1) gauge symmetry.

♣ The mass M can be computed from a string one-loop diagram and is given by a UV contact term.

• The physical mass is typically smaller than the string scale

$$M^2_{\text{phys}} = \quad g^2 M^2 \quad \sim \quad \alpha \, \frac{M_s^2}{V_{\text{internal}}}$$

• Therefore anomalous U(1)s are the first candidates to be seen from the "massive string states".

• A D-term-like potential is also generated.

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

• This important as EW Higgses are generically charged under anomalous U(1)'s

Some phenomenological considerations

• All orientifold realizations of the standard model contains one or more (typically 3) anomalous U(1)s, (beyond the $U(1)_Y$)

• One of them is gauged baryon number.

• In some vacua, another may be gauged lepton number

• If a third exists it is a gauged PQ type of symmetry.

♣For vacua with low M_s all three must exist!

Antoniadis+Kiritsis+Rizos+Tomaras, '00

• They can contribute to the $g-2$ of leptons.

Anastasopoulos and Kiritsis, 02

• They contribute and are constrained by data on the the ρ parameter.

Ghilencea+Ibanez+Irges+Quevedo, '02

• They mix with γ and Z_0 and this provides a new portal for their discovery. The full EFT has been developed.

Corriano+Irges+Kiritsis, '05

Anastasopoulos+Fucito+Lionetto+Pradisi+Racioppi+Stanev, '08

Couplings of anomalous U(1)'s

• Minimal couplings to standard model fermions

• Stuckelberg mass term. The mass varies from M_s to much smaller than M_s. Depends on the volumes wrapped by the D-brane. Sometimes it can become tiny.

• Axionic couplings to various $F \wedge F$ terms.

• The Higgs is charged under the PQ anomalous U(1): upon EW breaking, there is a mixing with the Z^0 and an additional contribution to the Z' mass.

• There are anomaly related couplings of the (gauge invariant) generalized Chern Simons terms

Anastasopoulos+Bianchi+Dudas+Kiritsis, '06

• These give rise to extra contributions to anomalous trilinear vertices.

Generalized Chern-Simons terms

• Non-anomalous U(1)s have GENERIC mixed anomalies with anomalous U(1)'s.

Anastasopoulos+Bianchi+Dudas+Kiritsis, '06

• If some linear combinations of U(1)s are non-anomalous (as we expect for the hypercharge in orientifold realizations of the SM) then, there are additional Chern-Simons-like couplings necessary for the cancellation of the anomalies.

Antoniadis+Kiritsis+Tomaras, '00
Anastasopoulos+Bianchi+Dudas+Kiritsis, '06

• Such couplings can be computed by a stringy computation and CANNOT always be inferred from anomaly cancellation.

• Similar effective couplings appear when an (anomalous) subset of massive fermions are integrated out.

D'Hoker+Farhi, '84

• In the context of Low-Scale Orientifold Models the presence of such couplings can have important experimental consequences. It induces couplings $Z^* \to Z\gamma$ and $Z' \to Z\gamma$, $Z' \to \gamma\gamma^*$ that may be visible at colliders.

Anastasopoulos+Bianchi+Dudas+Kiritsis, '06

The simplest example

- We consider a non-anomalous U(1), Y_μ with charge Y and an anomalous U(1) A_m with charge Q.

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

- The following mixed anomalies are NON-ZERO

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

We pick a symmetric scheme for the definition of the triangle graphs. Under a general gauge transformation

$$A_\mu \to A_\mu + \partial_\mu \epsilon \quad , \quad Y_\mu \to Y_\mu + \partial_\mu \zeta$$

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

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

To cancel it we write the general anomaly cancelling terms as before

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

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

- There is no mixing of Y_μ with an axion (unbroken Y-symmetry)

- The action above is NOT Y-gauge invariant and therefore not enough!

We must have Y-non-invariant terms.

$$L_{CS} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\left[D_4\ Y_\mu\ CS(A)_{\nu\rho\sigma} - D_5\ A_\mu\ CS(Y)_{\nu\rho\sigma}\right]$$

$$= \left[D_4\ Y \wedge A \wedge F^A - D_5\ A \wedge Y \wedge F^Y\right]$$

Now we may cancel the anomalies to obtain

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

• With more than one anomalous U(1) there are gauge invariant combinations of Generalized Chern Simons terms that cannot be inferred from low energy anomaly arguments.

• If A^i are anomalous U(1)s and Y^α are non-anomalous U(1)s, they are:

$$\mathcal{E}_{ijk}\int(da^i+A^i)\wedge(da^j+A^j)\wedge F_A^k+ \quad (1)$$

$$+\,\mathcal{E}_{ij\alpha}\int(da^i+A^i)\wedge(da^j+A^j)\wedge F_Y^\alpha \quad (2)$$

• $\mathcal{E}_{ijk}$ and $\mathcal{E}_{ij\alpha}$ must be computed in the UV theory.

Summary

- Anomalous U(1)s are ubiquitous in string theory.

- They are a necessary ingredient of any realization of the standard model.

- They are massive and anomaly cancellation proceeds through couplings to axions.

- They affect the physics of EW symmetry breaking as the Higgs is generically charged under them.

- There are new anomaly related terms (Generalized Chern Simons Terms) that are related to mixed anomalies with the hypercharge.

- They imply many novel effects for the standard model, whose implications have not yet been fully analyzed.

- Their potential role in astrophysics (dark matter) is currently explored, but their role in cosmology remains unexplored.

THANK YOU !

Bibliography

- REVIEW: Elias Kiritsis **Phys. Rept. 421 (2005) 105-190**

- Bottom up approach to string vacua

Antoniadis, Kiritsis, Rizos, Tomaras **hep-th/0210263 hep-th/0111269**, , **hep-ph/0004214**

- Large scale computerized search

Dijkstra, Huiszoon, Schellekens **hep-th/0403196**, **hep-th/0411129**

P. Anastasopoulos, T. Dijkstra E. Kiritsis, and B. Schellekens **hep-th/060522**

- EFT of Z's and triple gauge-boson couplings

C. Corianò, N. Irges, E. Kiritsis **Nucl. Phys. B746 (2006) 77-135**

P. Anastasopoulos, M. Bianchi, E. Dudas, E. Kiritsis **hep-th/0605225**

This research has been co-financed by the European Union (European Social Fund, ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF), under the grants schemes "Funding of proposals that have received a positive evaluation in the 3rd and 4th Call of ERC Grant Schemes" and the program "Thales"

Supersymmetry

- Supersymmetry seems necessary for the perturbative stability of string vacua

- Supersymmetry breaking can be handled in the effective field theory

- In most approaches that break supersymmetry the (large) vacuum energy is “neglected”

Where is the string scale

In view of all this what is the right strategy?

• If $M_s \sim 1 - 100$ TeV stringy physics is accessible at colliders. The correct vacuum can be found via an interplay between theory and data.

This involves large internal volumes, and it is not generic. It can be achieved however via moduli stabilisation at large volumes $\left(M_s = \frac{M_P}{\sqrt{V_6}}\right)$

Conlon+Quevedo+Suruliz

♣If $M_s \sim 10^{16}$ GeV There is no chance of seeing stringy physics at colliders.

Hints may be obtained from cosmology. But EFT is the only reasonable approach. Embedding a successful CFT in ST may be just not an academic exercise, at least for cosmology

♠We have no clue as to how much M_s could be.

Classification of hypercharge embeddings

$$Y = \left(x - \frac{1}{3}\right) Q_a + \left(x - \frac{1}{2}\right) Q_b + x Q_C + (x-1)\, Q_D$$

C,D are distributed on the c,d brane-stacks.

The following is exhaustive: (Allowed values for x)

- $x = \frac{1}{2}$: Madrid model, Pati-Salam, flipped-SU(5)+broken versions, model C of AD.
- $x = 0$: SU(5)+broken versions, AKT low-scale brane configurations, A,A'
- $x = 1$: AKT low-scale brane configurations, B,B'
- $x = -\frac{1}{2}$: None found
- $x = \frac{3}{2}$: None found
- $x =$arbitrary: Trinification (x=1/3). Some fixed by masslessnes of Y

Realizations: our terminology

BOTTOM-UP configurations:choosing the gauge group, postulating particles as open strings, imposing generalized cubic anomaly cancelation, and ignoring particles beyond the SM, as in the example

Antoniadis+Kiritsis+Tomaras

TOP-DOWN configurations: Configurations constructed in the Gepner model setup, satisfying all BCFT criteria but for tadpole cancellation.

STRING VACUA: TOP-DOWN configurations with tadpoles solved. This is achieved by varying the hidden sector.

(Conventional) Unification

- $a = b$:$\rightarrow$ SU(5) and flipped SU(5) variants.

- $a = c$:$\rightarrow$ Simplest is Pati-Salam $U(4)\times U(2)\times U(2)$

- $b = c$: $\rightarrow$ Trinification $U(3) \times U(3) \times U(3)$

- $a = b = d$: $\rightarrow$ An $U(6) \times Sp(2)$ hyperunification

Results of the search

♠ $\sim 10^{20}$ distinct configurations (SM spectra) were searched not including the hidden sector.

Anastasopoulos+Dijkstra+Huiszoon+Schellekens

♠ There a priori an infinite number of bottom-up constructions. Even fixing some small number of non-chiral exotics the number is much larger than Top-down.

♠ 19345 different SM embeddings (Top-down constructions) were found.

♠ Tadpoles were solved in 1900 cases (as usual there is a 1 % chance of solving the tadpoles)

♠ One hypercharge embedding dominates by far all other ones (the "Madrid" embedding).

♠The first examples of SU(5) and flipped SU(5) orientifold vacua were produced with the correct chiral spectrum (no hidden gauge group and no chiral exotics).

♠Minimal Pati-Salam and trinification vacua were found.

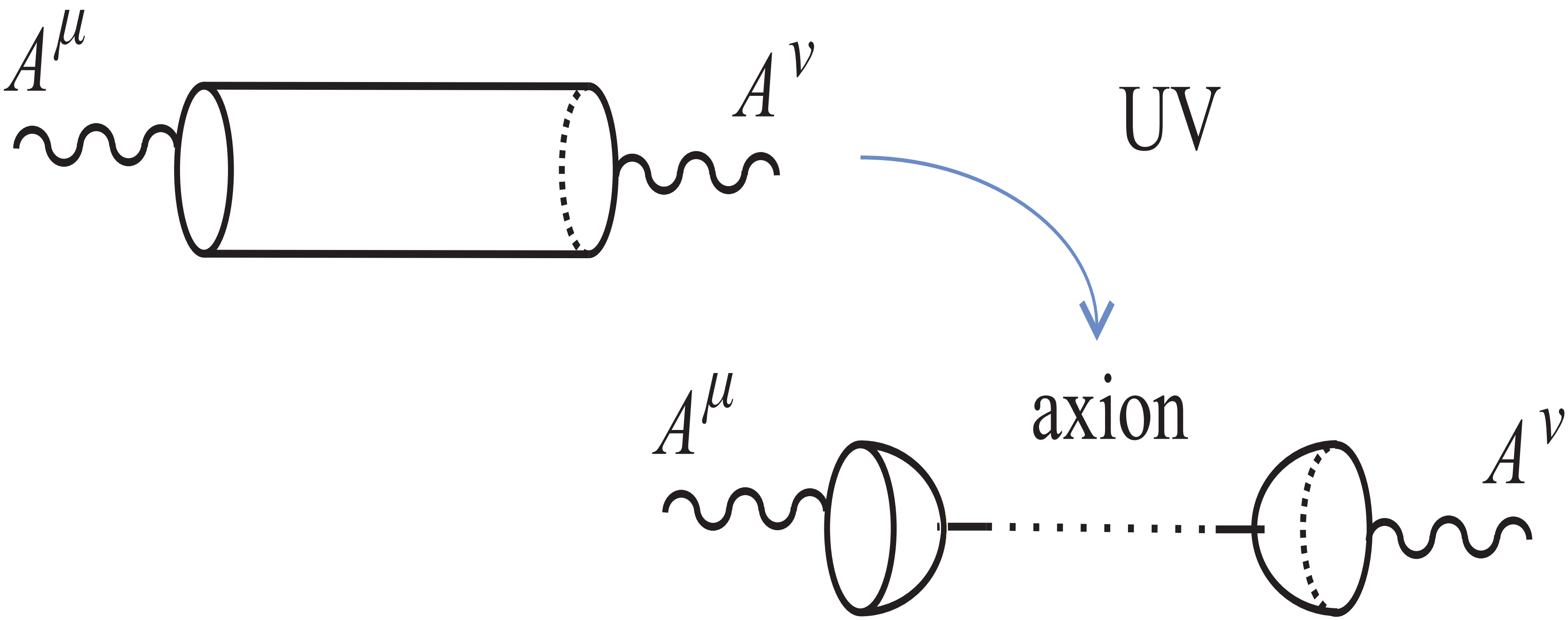
Anomalous U(1) masses

♡ The Stückelberg term in the action,

$$\frac{1}{2}(\partial_\mu a + M\ A_\mu)^2$$

mixing the U(1) gauge boson and the axion gives mass to the anomalous gauge-boson and breaks the U(1) gauge symmetry.

♣ The ultraviolet mass M can be computed from a string one-loop diagram and is given by a UV contact term.



Antoniadis, Kiritsis, Rizos

If the gauge boson belongs to a D-brane, D, and the associated axion is localized on a orbifold plane P, the mixing term scales as

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

• The D-term-like potential is of the form

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

This important as it implies that EW Higgses are charged under anomalous U(1)'s

Generalized cubic anomaly cancelation

Cubic (four-dimensional) anomalies exist for groups with compex representations (SU(N), O(6) etc).

For SU(N), $A(\bar{R}) = -A(R)$

$$A(\square) = 1 \quad , \quad A\left(\begin{smallmatrix}\square\\\square\end{smallmatrix}\right) = N-4 \quad , \quad A(\square\square) = N+4 \quad , \quad A(\text{adjoint}) = 0$$

Standard U(1) anomalies $Tr[Q] \neq 0$ and $Tr[Q^3] \neq 0$ are cancelled by the Green-Schwarz-Sagnotti mechanism.

But, the "anomaly" for U(N) applies also for N=2 and N=1!!!!

Example 1: U(1): $5\,\square_1$ and $\overline{\square\square}_{-2}$ is an anomaly free combination.

Example 2: U(1): $3\,\square_1$ and $\begin{smallmatrix}\square\\\square\end{smallmatrix}_{\,2}$ is an anomaly free combination. Note that A is not massless!

Example 3: U(2): $2\,\square + \begin{smallmatrix}\square\\\square\end{smallmatrix}_{\,2}$ is anomaly free. Note that the second is an SU(2) singlet.

RETURN

“Popular” hypercharge embeddings

Four-stack low-scale models: $U(3) \times U(2) \times U(1) \times U(1)$

• Models A,A' (x=0) $Y = -\frac{1}{3}Q_a + \frac{1}{2}Q_b + Q_c$.

Antoniadis+Kiritsis+Tomaras

More complicated versions found

• Models B,B' (x=1) $Y = \frac{2}{3}Q_a - \frac{1}{2}Q_b + Q_c$.

Antoniadis+Kiritsis+Tomaras

A $U(3) \times U(2) \times U(2) \times U(1)$ variant was found. This is VERY rare

• Madrid embedding: $\left(x = \frac{1}{2}\right)$: $Y = \frac{1}{6}Q_a + \frac{1}{2}Q_c + \frac{1}{2}Q_d$

Ibanez+Marchesano+Rabadan

Three-stack bottom-up models $U(3) \times U(2) \times U(1)$

• Model A: (x=0) $Y = -\frac{1}{3}Q_a + \frac{1}{2}Q_b$. SU(5) spectrum (many found)

Antoniadis+Dimopoulos

• Models B,C:(x=1) $Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c$: B→ flipped SU(5) (many found)

Antoniadis+Dimopoulos

A variant of C : $U(3) \times Sp(2) \times U(1)$ was found, as a top-down construction.

(Minimal) Low string scale orientifold vacua (MLSO)

The previous discussion becomes interesting when the massive anomalous U(1) gauge bosons are sufficiently close to experiment.

This happens when the string scale is low ($\sim$ TeV)

Then, extra U(1) gauge bosons are the generic low energy signals of orientifold models.

Anastasopoulos, Kiritsis
Ghilencea, Ibanez, Irges, Quevedo
Antoniadis, Kiritsis, Rizos, Tomaras

We take two of the six compact directions to be large. We wrap only the U(1)' brane around them (for the sake of getting light neutrinos)

The charge assignments for the SM particles are parameterized as:

SM particle	$U(1)_3$	$U(1)_2$	$U(1)$	$U(1)'$
$Q(\mathbf{3},\mathbf{2},+\frac{1}{6})$	$+1$	w	0	0
$u^c(\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	-1	0	a_1	a_2
$d^c(\bar{\mathbf{3}},\mathbf{1},+\frac{1}{3})$	-1	0	b_1	b_2
$L\ (\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$+1$	c_1	c_2
$e^c(\mathbf{1},\mathbf{1},+1)$	0	0	d_1	d_2
$H_u\ (\mathbf{1},\mathbf{2},+\frac{1}{2})$	0	$-w$	c_3	c_4
$H_d\ (\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$-w$	c_5	c_6
$\nu^c(\mathbf{1},\mathbf{1},0)$	0	0	d_1	d_2

♣ The charges are assigned using the principle that each end-point has charges ± 1

♣ Baryon number is a gauged symmetry namely, $U(1)_3$

♣ We must require that Lepton number is also a good symmetry

♣ The hypercharge must be a linear combination of the 4 U(1) factors:

$$Y = k_3 Q_3 + k_2 Q_2 + k_1 Q_1 + k'_1 Q'_1$$

Since U(1)' wraps large dimensions, to avoid a tiny α_Y we must take $k'_1 = 0$.

After taking into account also the matching of the gauge coupling constants there four possible configurations

Antoniadis, Kiritsis, Rizos, Tomaras

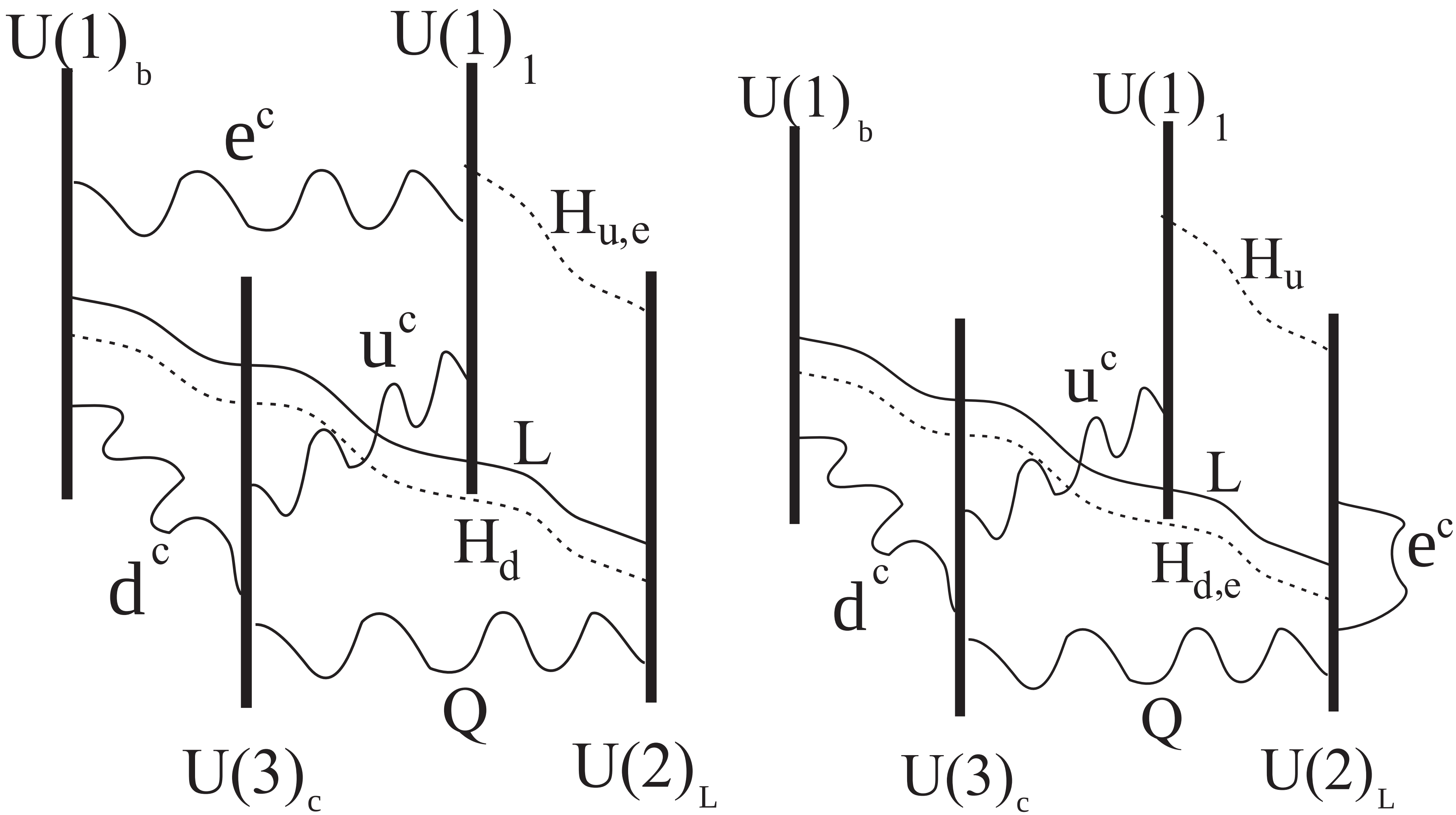
Models mLSO$_A$ and mLSO$_{A'}$

SM particle	$U(1)_3$	$U(1)_2$	$U(1)$	$U(1)'$
$Q(\mathbf{3},\mathbf{2},+\frac{1}{6})$	$+1$	-1	0	0
$u^c(\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	-1	0	-1	0
$d^c(\bar{\mathbf{3}},\mathbf{1},+\frac{1}{3})$	-1	0	0	-1
$L\ (\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$+1$	0	-1
$e^c(\mathbf{1},\mathbf{1},+1)$	0	0(2)	1(0)	1(0)
$H_u\ (\mathbf{1},\mathbf{2},+\frac{1}{2})$	0	1	1	0
$H_d\ (\mathbf{1},\mathbf{2},+\frac{1}{2})$	0	-1	0	-1
$\nu^c(\mathbf{1},\mathbf{1},0)$	0	0	0	± 2

$$Y = -\frac{1}{3}Q_3 - \frac{1}{2}Q_2 + Q_1$$

Lepton Number $\quad L = \frac{1}{2}(Q_3 + Q_2 - Q_1 - Q_1')$

Peccei – Quinn $\quad PQ = -\frac{1}{2}(Q_3 - Q_2 - 3Q_1 - 3Q_1')$


U(1)_b
U(1)_1
e^c
H_{u,e}
u^c
L
H_d
d^c
Q
U(3)_c
U(2)_L
U(1)_b
U(1)_1
H_u
u^c
L
e^c
H_{d,e}
d^c
Q
U(3)_c
U(2)_L

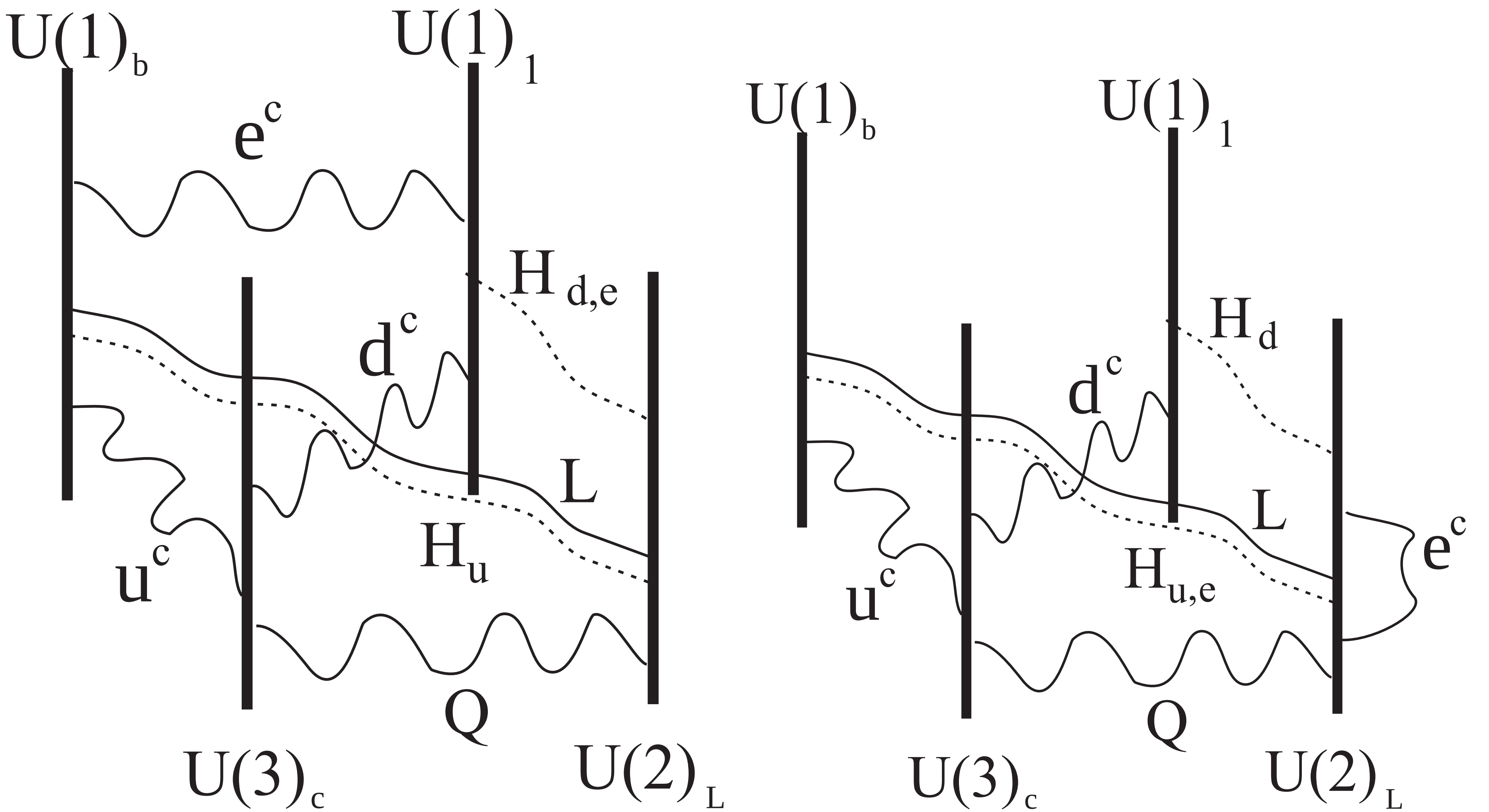
Models mLSO$_B$ and mLSO$_{B'}$

SM particle	$U(1)_3$	$U(1)_2$	$U(1)$	$U(1)'$
$Q(\mathbf{3},\mathbf{2},+\frac{1}{6})$	$+1$	-1	0	0
$u^c(\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	-1	0	0	1
$d^c(\bar{\mathbf{3}},\mathbf{1},+\frac{1}{3})$	-1	0	1	0
$L\ (\mathbf{1},\mathbf{2},-\frac{1}{2})$	0	$+1$	0	-1
$e^c(\mathbf{1},\mathbf{1},+1)$	0	0(2)	1(0)	1(0)
$H_u\ (\mathbf{1},\mathbf{2},+\frac{1}{2})$	0	-1	0	-1
$H_d\ (\mathbf{1},\mathbf{2},+\frac{1}{2})$	0	1	1	0
$\nu^c(\mathbf{1},\mathbf{1},0)$	0	0	0	± 2

$$Y = \frac{2}{3}Q_3 - \frac{1}{2}Q_2 + Q_1$$

Lepton Number $\quad L = -\frac{1}{2}(Q_3 - Q_2 + Q_1 + Q_1')$

Peccei – Quinn $\quad PQ = \frac{1}{2}(-Q_3 + 3Q_2 + Q_1 + Q_1')$



U(1)b
U(1)l
e^c
H d,e
d^c
L
H u
u^c
Q
U(3)c
U(2)L
U(1)b
U(1)l
H d
d^c
L
e^c
H u,e
u^c
Q
U(3)c
U(2)L

The anomalous U(1)s

In all four models above, we can label the fours U(1)s as:

Y= Hypercharge

B= Baryon Number

L= Lepton Number

PQ= Peccei-Quinn-like symmetry

They have a non-trivial anomaly structure as in the cases we described earlier We will therefore have CS terms of the structure described

$$L_{CS} = E_{ijk}\ A^i \wedge A^j \wedge F^k \quad , \quad i,j,k \in (Y,B,L,PQ)$$

EW Symmetry breaking

The two EW Higgses are charged under Y and PQ but not B and L.

When EW breaking happens, both Y and PQ are spontaneously broken.

• There must be PQ violating terms in the potential otherwise a massless Goldstone boson (axion) remains with couplings that cannot be made small. This can be achieved by moving off the orientifold point.

There are in general two origins for the mass of the various gauge bosons:

♣ The UV mass-matrix of the anomalous U(1)s coming from

$$\sum_I (\partial_\mu a^I + B_i^I A_\mu^i)^2 \quad , \quad M_{ij}^2 = \sum_I B_i^I B_j^I$$

It can be obtained from a string calculation. Its eigenvalues are typically a half– a tenth of the string scale.

♠ The Higgs expectation value $v \simeq 100 - 200$ GeV

Signals at colliders

• The three massive Z' associated to PQ, B, L have the standard Z' related couplings to the fermions.

• They can be seen in LHC if their masses are lower than 5 TeV in $pp \to Z' \to \ell^+\ell^-$. More detailed info can be obtained from the Forward-Backward asymmetry for masses up to 2 TeV.

Dittmar, Nicollerat, Djouadi

• The current experimental limit $\Gamma(Z^0 \to \gamma\gamma)/M_Z^0 \leq 5 \times 10^{-7}$ puts a (mild) lower bound on M_s from the anomaly-induced $Z^0 \to \gamma\gamma$ vertex. It will be interesting if this signal can be seen directly. (This vertex avoids the Landau-Yamg theorem because it is not gauge invariant!)

• There is also a new vertex that will give two Z^0s in the DY channel $pp \to \gamma \to Z^0 Z^0$ For LHC energies this of the same order of magnitude as the $pp \to Z^0 \to \gamma\gamma$ process.

The Z' gauge bosons have also non-standard anomaly related couplings that distinguish them from other Z' models.

• There are O(1) couplings that provide new production channels apart

from DY, namely

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

• Moreover, the first signal is expected to be stronger than the $Higgs \to \gamma\gamma$ signal, that is one of the main channels for the discovery of the Higgs

Z-Z' mixing

Anastasopoulos+Kiritsis, Kors+Nath

After the Higgs mechanism, the three mass eigenstates, the photon A, the Z^0, and the PQ-related Z'-boson, are specific linear combinations of W^3, Y and PQ gauge bosons. Inversely

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

We have

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

The ρ-parameter, $\rho = \frac{M_W^2}{M_Z^2 \sin\theta_W}$, is no more equal to the standard model value

$$\frac{\Delta\rho}{\rho_0} \sim \frac{M_Z}{M_s} < 6 \times 10^{-4}$$

and there are small modifications of the Z^0 couplings to the fermions.
RETURN

Ghilencea, Ibanez, Irges, Quevedo

Trilinear couplings

Consider now the various anomaly cancelling Chern-Simons-like terms.

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

Similarly for the other relevant CS term $Y \wedge PQ \wedge dPQ$.

RETURN

Detailed plan of the presentation

- Supersymmetry
- Where is the string scale
- Classifications of hypercharge embeddings
- Realizations: our terminology
- Conventional Unification
- Results of the search
- Anomalous U(1) masses
- Generalized cubic anomaly cancelation
- "Popular" hypercharge embeddings
- (Minimal) Low string scale orientifold vacua (MLSO) 3 minutes
- Models mLSO_A and $\text{mLSO}_{A'}$ 3 minutes
- Models mLSO_B and $\text{mLSO}_{B'}$ 3 minutes
- The anomalous U(1)s 3 minutes
- EW Symmetry breaking 3 minutes
- Signals at colliders 3 minutes
- Z-Z' mixing
- Trilinear couplings