RR photons

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with L. E. Ibáñez and F. Marchesano, arXiv:**1106.0060** [hep-th].

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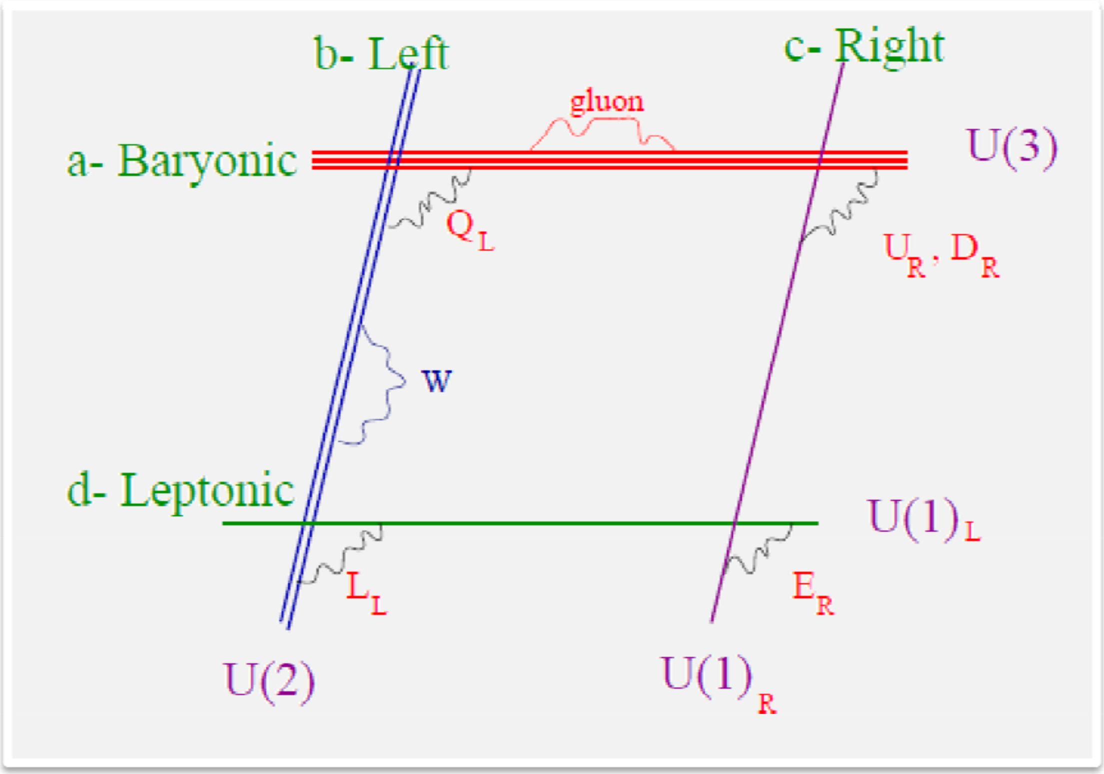
1. Motivation

String theory compactifications with a semi-realistic spectrum generically lead to U(1) gauge symmetries beyond $U(1)_Y$



[Cremades, Ibanez, Marchesano ’02]

1. Motivation

• Some of these extra U(1) gauge symmetries acquire masses via the Stückelberg mechanism

$$\mathcal{L} \supset C_2 \wedge F_2 \quad \Rightarrow \quad \mathcal{L}_{\rm Stk} = \frac{1}{2}(d\rho + qA)^2 \qquad (d\rho = *_4 dC_2)$$

$M_{U(1)_X} \sim M_s$ ⇒ global symmetries

broken by non-perturbative effects to discrete subgroups (e.g. matter parity, baryon triality...)

[Berasaluce et al. '11]

Only detectable at experiments if M_s ~ 1 TeV (WIMPs)

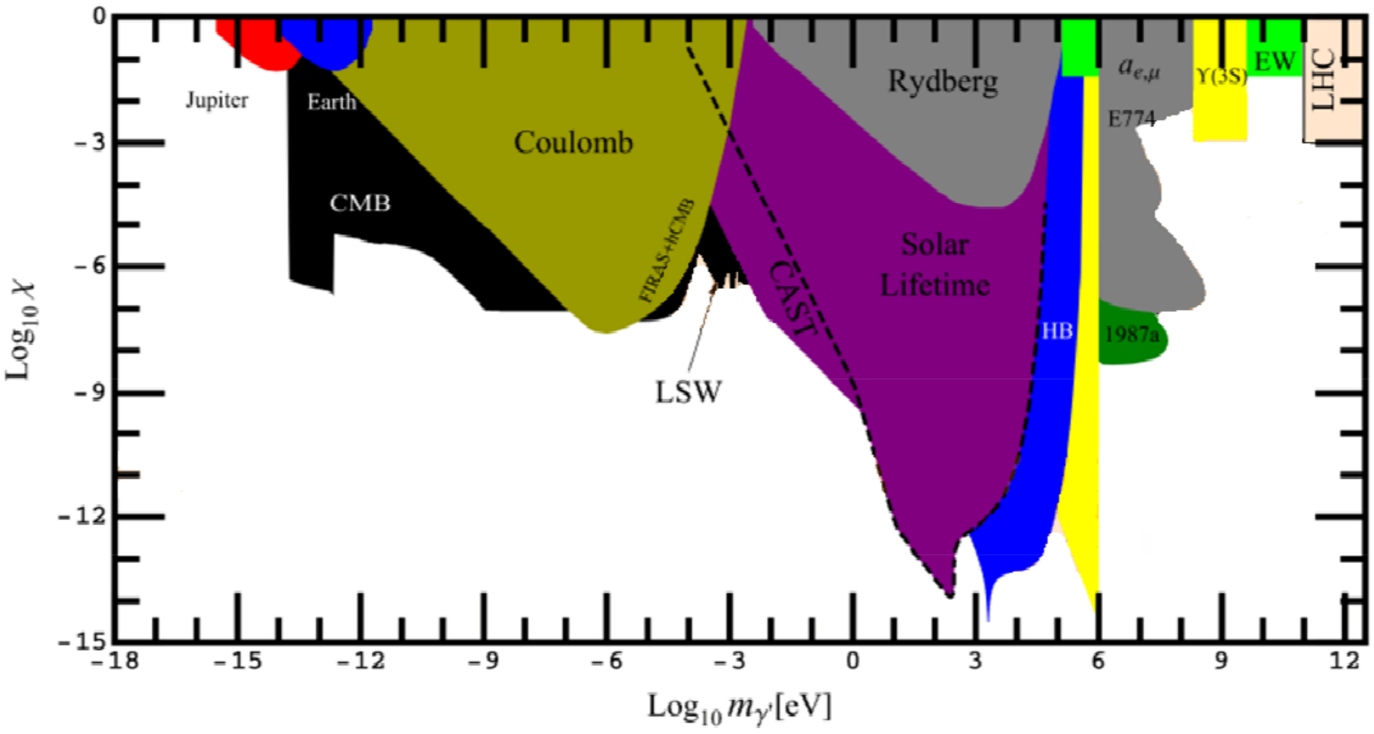
[Ghilencea et al. '02]

• Other U(1)'s however may remain massless or very light (WISPs) and lead to light hidden U(1) gauge symmetries.

1. Motivation

Light hidden U(1) gauge symmetries are a window of opportunity to hidden sector physics, even at large string scale

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}X_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 X_\mu X^\mu$$

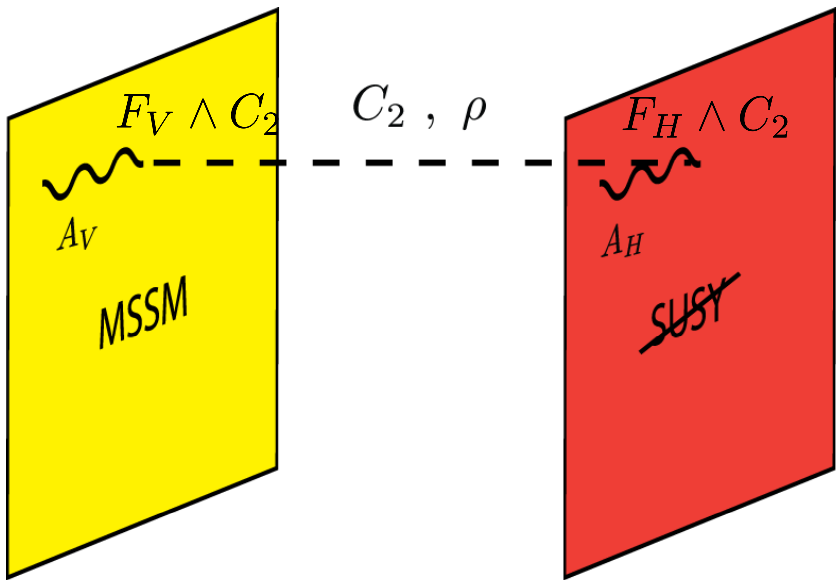


[Jaeckel, Ringwald ’10]

1. Motivation

• Hidden U(1)'s are also a possible mechanism for mediating SUSY breaking in a flavor independent way:

[Langacker et al '07]
[Verlinde et al. '07]



$$\mathcal{L} \supset \frac{1}{2}|d\rho + eA_V + qA_H|^2$$

⇒

$$A_Y \sim eA_V - qA_H$$
$$A_X \sim eA_V + qA_H$$

1. Motivation

In type II string theory compactifications there are two sources of hidden U(1) gauge symmetries:

- D-branes located 'far away' from the MSSM D-brane sector

- Bulk U(1)'s arising from KK reduction of the Ramond-Ramond closed string fields ⇨ no massless matter charged under them

It is therefore natural to ask:

- *Can RR U(1)'s mix with the hypercharge??*
- *If so, can we compute* χ *and* $m_{\gamma'}$ *??*
- *Can we obtain new phenomenological scenarios ??*

1. Motivation

- *Can RR U(1)'s mix with the hypercharge??*
- *If so, can we compute* χ *and* $m_{\gamma'}$ *??*
- *Can we obtain new phenomenological scenarios ??*

Moreover, the distinction between RR and D-brane U(1)'s is arbitrary at strong coupling: in M-theory / F-theory both correspond to KK U(1)'s

Another related question is therefore:

- Is there a geometric understanding of the Stuckelberg mechanism??

Outline of the talk

1. U(1)'s in type IIA compactifications
2. 'Kinetic mixing' with RR photons
3. 'Mass mixing' with RR photons
4. Some phenomenological implications
5. The unified M-theory picture
6. Concluding remarks

2. U(1)'s in type IIA compactifications

Type IIA string theory on a CY orientifold $\mathbb{R}^{1,3} \times \mathcal{M}_6/\Omega_p(-1)^{F_L}\sigma$

$$\sigma J = -J \ , \qquad \sigma\Omega = \overline{\Omega}$$

• **Closed string spectrum:** one-to-one correspondence between massless 4d closed-string fields and harmonic forms

$h_-^{1,1} + h^{1,2} + 1$	*N = 1 chiral multiplets*
$h_+^{1,1}$	*N = 1 vector multiplets*

2. U(1)'s in type IIA compactifications

$h_{-}^{1,1} + h^{1,2} + 1$ *N = 1 chiral multiplets*

Scalar components parametrize compactification moduli space:

$$J_c \equiv B_2 + iJ = T^{\hat{i}} \omega_{\hat{i}} \ , \qquad \Omega_c \equiv C_3 + i\mathrm{Re}(C\Omega) = N^I \alpha_I$$

Real parts of complex structure moduli ⇨ axions

- Invariant under shift symmetries
- Can participate in Stückelberg mechanism

Dual 2-forms: $C_5 = \sum_I C_2^I \wedge \beta^I + \ldots$

2. U(1)'s in type IIA compactifications

$h_{+}^{1,1}$ *N = 1 vector multiplets*

RR U(1) gauge bosons from the expansions:

$$C_3 = \sum_I \mathrm{Re}(N^I)\alpha_I + \sum_i A^i \wedge \omega_i$$

Dual magnetic d.o.f. from C_5

Gauge kinetic function [Grimm, Louis '04]

$$f_{ij} = -i\mathcal{K}_{ij\hat{k}} T^{\hat{k}}$$

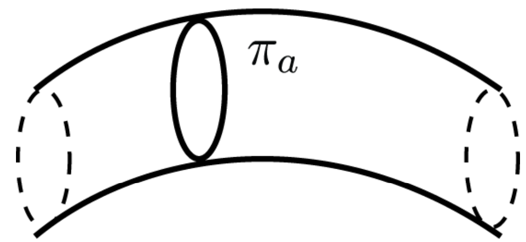
Each massless $U(1)_{RR}$ has an element of $H_2^+(\mathcal{M}_6, \mathbb{R})$ associated to it.

2. U(1)'s in type IIA compactifications

D6-brane N = 1 vector & chiral multiplets

D6-branes wrap special Lagrangian 3-cycles in the CY

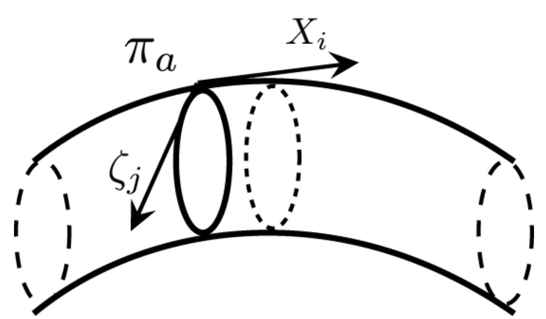
$$J|_{\pi_a} = 0 \,, \qquad \mathrm{Im}(\Omega)|_{\pi_a} = 0$$



Standard Model located in this sector

N_a D6-branes ⇨ $SU(N_a) \times U(1)_a$ $\qquad f_a = -iN_a \int_{\pi_a} \Omega_c$

Deformations preserving sLag parametrized by $b_1(\pi_a)$ open string moduli:



[McLean '98]

$$\Phi_a^j = \theta_a^j + \lambda_i^j \phi_a^i$$

$$\theta_a = \theta_a^j \zeta_j, \quad \phi_a = \phi_a^i X_i, \quad \iota_{X_i} J_c|_{\pi_a} = \lambda_i^j \zeta_j$$

2. U(1)'s in type IIA compactifications

D6-brane N = 1 vector & chiral multiplets

There is a Stückelberg mechanism for some of the D6-brane U(1)'s:

$$\int_{\mathbb{R}^{1,3}\times\pi_a} C_5 \wedge F_2^a = -c_a^I \int_{\mathbb{R}^{1,3}} C_2^I \wedge F_2^a \quad \Rightarrow \quad Q^I = \sum_a c_a^I N_a Q^a \quad \text{is massive}$$

$$c_a^I = -\int_{\pi_a} \beta^I$$

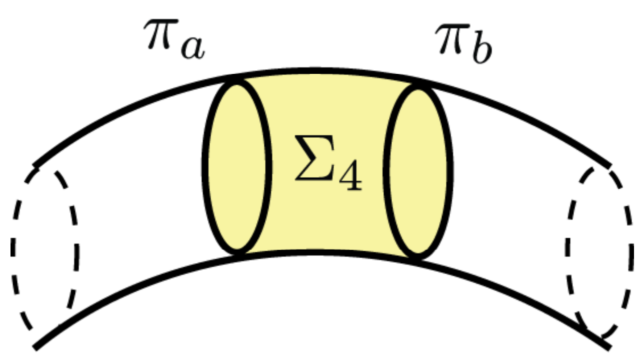
Nice interpretation geometric interpretation. Each D6-brane $U(1)_a$ gauge symmetry has an element of $H_3^-(\mathcal{M}_6, \mathbb{R})$ associated to it, $\pi_a - \pi_a^*$

$$Q^b = \sum_a n_a^b Q^a \quad \text{massless} \quad \Leftrightarrow \quad \pi_b^- = \sum_a n_a^b N_a(\pi_a - \pi_a^*) \quad \text{trivial}$$

$$(\partial\Sigma_4 = \pi_b^-)$$

2. U(1)'s in type IIA compactifications

D6-brane N = 1 vector & chiral multiplets

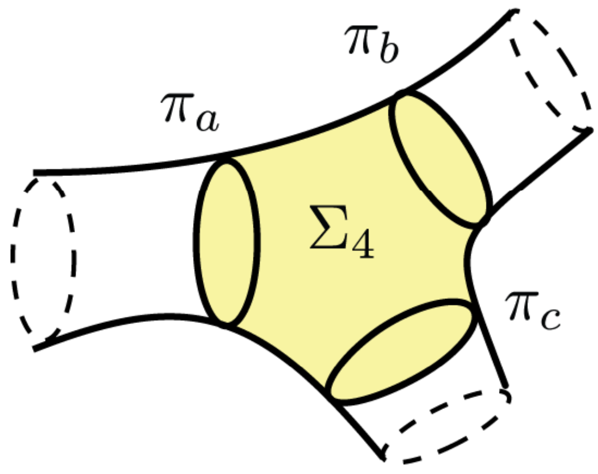


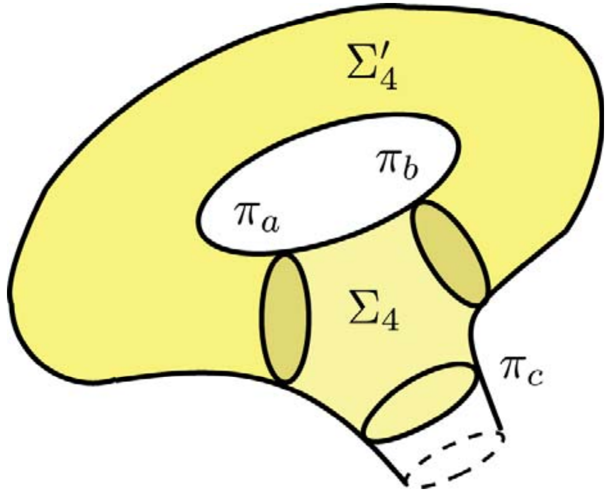
$$\partial\Sigma_4 = \pi_a - \pi_b$$

$$U(2) \to U(1)_a \times U(1)_b$$

$U(1)_a - U(1)_b$ massless

$U(1)_a + U(1)_b$ massive





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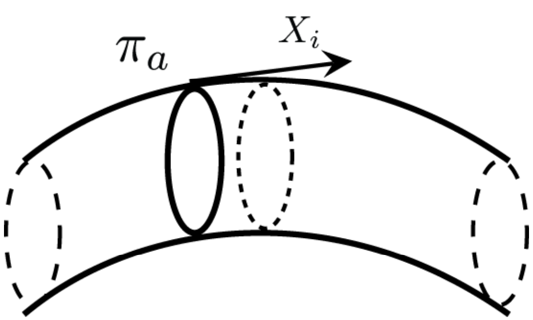
3. Kinetic mixing with RR photons

Can D6-brane and RR U(1)'s mix kinematically ??

$$S_{4\text{d,mix}} = -\int_{\mathbb{R}^{1,3}} \left[\text{Re}(f_{ia}) F^i_{\text{RR}} \wedge *_4 F^a_2 + \text{Im}(f_{ia}) F^i_{\text{RR}} \wedge F^a_2\right]$$

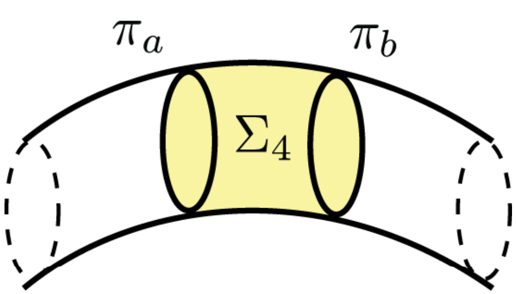


From the D6-brane CS action:

$$\mathcal{F}^a_2 \wedge C_5 + \frac{1}{2}\mathcal{F}^a_2 \wedge \mathcal{F}^a_2 \wedge C_3 \quad \Rightarrow \quad f_{ia} = \Phi^j_a \int_{\pi_a} \omega_i \wedge \zeta^j + \ldots$$

Requires non-trivial 2-cycle in π_a and $\mathcal{M}_6$

Well-defined for massless U(1)'s:



$\partial\Sigma_4 = \pi_a - \pi_b$

$$f_{i(a-b)} = (\Phi^j_a - \Phi^j_b) \int_{\rho_j} \omega_i + \ldots \quad \Rightarrow \quad f_{ib} = \int_{\Sigma_4} (J_c + F^b_2) \wedge \omega_i$$

4. Mass mixing with RR photons

We have seen the following U(1) charge assigment:

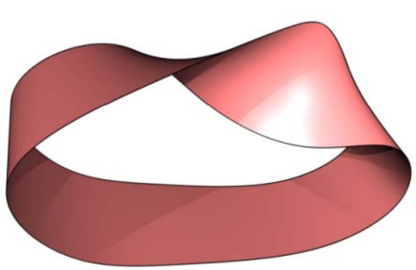
$H_3^-(\mathcal{M}_6,\mathbb{R})$ ⇨ D6-brane U(1)'s

$H_2^+(\mathcal{M}_6,\mathbb{R})$ ⇨ RR U(1)'s

But shouldn't be $H_r(\mathcal{M}_6,\mathbb{Z})$ the relevant classes??

$$H_r(\mathcal{M}_6,\mathbb{Z}) = \underbrace{\mathbb{Z}\oplus\ldots\oplus\mathbb{Z}}_{b_r}\oplus\mathbb{Z}_{k_1}\oplus\ldots\oplus\mathbb{Z}_{k_n}$$

$$\partial\Sigma_{r+1} = k\pi_r^{\rm tor}$$



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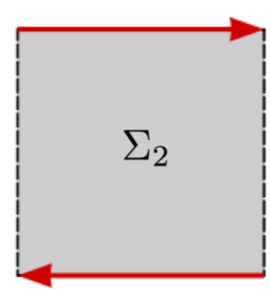


$$H_1(\mathcal{M},\mathbb{Z}) = \mathbb{Z}_2$$

Torsional cycles cannot be detected by 4d massless fields because

$$\int_{\pi_r^{\rm tor}}\omega_r = \frac{1}{k}\int_{\Sigma_{r+1}} d\omega_r = 0$$

4. Mass mixing with RR photons

Some useful results in algebraic topology (UCT + Poincaré duality):

$$\mathrm{Tor}\, H_3(\mathcal{M}_6, \mathbb{Z}) \simeq \mathrm{Tor}\, H_2(\mathcal{M}_6, \mathbb{Z})$$

$$\mathrm{Tor}\, H_1(\mathcal{M}_6, \mathbb{Z}) \simeq \mathrm{Tor}\, H_4(\mathcal{M}_6, \mathbb{Z})$$

D2-brane wrapping π_2^{tor} ⇒ 4d particle

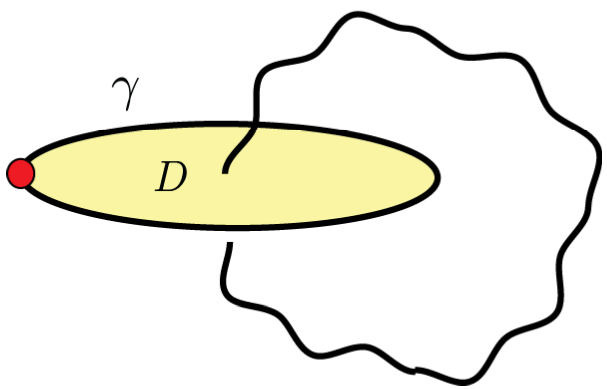
D4-brane wrapping π_3^{tor} ⇒ 4d string

Non-BPS objects in 4d, but stable mod k

Aharanov-Bohm strings and particles [Alford, Krauss, Wilczek '89]

4. Mass mixing with RR photons

$$dF_4 = \delta_5$$



They satisfy $\mathbb{Z}_k$ holonomies:

$$\frac{1}{2\pi i}\log\left[\mathrm{hol}(\gamma,[\pi_2^{\mathrm{tor}}])\right] \overset{\mathrm{mod}\,1}{=} \frac{1}{k}\int_{D\times k\pi_2^{\mathrm{tor}}} F_4 = \frac{1}{k}\int_{D\times\Sigma_3}\delta_5 = \frac{p}{k}$$

Linking number $\overset{\mathrm{mod}\,1}{\equiv} L([\pi_2^{\mathrm{tor}}],[\pi_3^{\mathrm{tor}}])$

A-B strings and particles are the smoking gun of massive U(1)’s higgsed down to a discrete $\mathbb{Z}_k$ gauge symmetry via the Stuckelberg mechanism

[Banks, Seiberg ’10]

We can see this more explicitly from dimensional reduction.

4. Mass mixing with RR photons

For that we introduce the set of forms which correspond to the generators of $\mathrm{Tor}\ H^4(\mathcal{M}_6) \simeq \mathrm{Tor}\ H_3(\mathcal{M}_6)$ and $\mathrm{Tor}\ H^3(\mathcal{M}_6) \simeq \mathrm{Tor}\ H_2(\mathcal{M}_6)$

$$d\omega_\alpha^{\mathrm{tor}} = k_\alpha{}^\beta \alpha_\beta^{\mathrm{tor}} \ , \quad d\beta^{\mathrm{tor},\beta} = -k^\beta{}_\alpha \tilde{\omega}^{\mathrm{tor},\alpha} \quad L([\pi_{2,\alpha}^{\mathrm{tor}}],[\pi_3^{\mathrm{tor},\beta}]) = (k^{-1})_\alpha{}^\beta$$

Expanding in these,

$$C_3 = \sum_\alpha \mathrm{Re}(N^\alpha)\alpha_\alpha^{\mathrm{tor}} + A^\alpha \wedge \omega_\alpha^{\mathrm{tor}} + \ldots$$

$$dC_3 = [\mathrm{Re}(dN^\beta) + k^\beta{}_\alpha A^\alpha] \wedge \alpha_\beta^{\mathrm{tor}} + dA^\alpha \wedge \omega_\alpha^{\mathrm{tor}} + \ldots$$

Massive RR U(1) gauge symmetries

Electric charges: A-B particles

Magnetic charges: A-B strings

4. Mass mixing with RR photons

Massless RR U(1)'s

$$H_2^+(\mathcal{M}_6, \mathbb{R})$$

Hodge duality: $H_2^+(\mathcal{M}_6, \mathbb{R}) \simeq H_4^-(\mathcal{M}_6, \mathbb{R})$

Intersection number

Electric charges: D2 (4d particles)

Magnetic charges: D4 (4d monopoles)

$U(1)$ gauge symmetry

Massive RR U(1)'s

$$\mathrm{Tor}\ H_2^+(\mathcal{M}_6, \mathbb{Z})$$

UCT+Poinc.: $\mathrm{Tor}\, H_2^+(\mathcal{M}_6, \mathbb{Z}) \simeq \mathrm{Tor}\, H_3^-(\mathcal{M}_6, \mathbb{Z})$

Linking number

Electric charges: D2 (4d A-B particles)

Magnetic charges: D4 (4d A-B strings)

$\mathbb{Z}_k$ gauge symmetry

$$H_2^+(\mathcal{M}_6, \mathbb{Z})$$

4. Mass mixing with RR photons

Can D6-brane and RR U(1)'s mix through the Stuckelberg mechanism ??

We have seen that a D4-brane wrapping a torsional 3-cycle

$$[\pi_b^-] = \sum_\beta c_b^\beta [\pi_3^{\mathrm{tor},\beta}]$$

develops a coupling,

$$S_{4d} \supset \sum_\beta c_b^\beta \int_{\mathbb{R}^{1,3}} C_2^\beta \qquad\qquad C_2^\beta \equiv \int_{\pi_3^{\mathrm{tor},\beta}} C_5$$

Similarly, a D6-brane wrapping the same 3-cycle develops a Stuckelberg coupling in its worldvolume,

$$-\sum_\beta c_b^\beta \int_{\mathbb{R}^{1,3}} C_2^\beta \wedge F_2^b$$

It can also be seen from dim. reduction of the CS D6-brane action

Therefore, massive RR U(1)'s couple to the same complex structure axions than D6-branes do.

4. Mass mixing with RR photons

Massive RR U(1)'s therefore may mix with D6-brane U(1)'s.

$$Q^I = \sum_a c_a^I N_a Q^a$$

$$Q^\beta = \sum_\alpha k^\beta{}_\alpha Q^\alpha_{RR} + \sum_a c_a^\beta N_a Q^a$$

Each linear combination of D6-brane and torsional RR U(1) gauge symmetries has an element of $H_3^-(\mathcal{M}_6, \mathbb{Z})$ associated to it. Massless combinations of U(1)'s are trivial elements in *integer* homology.

$$Q_0 = \sum_a n_a Q^a + \sum_\alpha \check{n}_\alpha Q^\alpha_{RR} \quad \text{massless}$$

$$\Updownarrow$$

$$\sum_a \frac{N_a n_a}{2}([\pi_a] - [\pi_a^*]) + \sum_{\alpha,\gamma} \check{n}_\alpha k^\alpha{}_\gamma [\pi_3^{\mathrm{tor},\gamma}] = 0$$

Elements which are also trivial in de Rham do not mix with RR U(1)'s

5. Some phenomenological implications

Some examples: Type IIA orientifold of the Enriques CY

[Aspinwall '95]

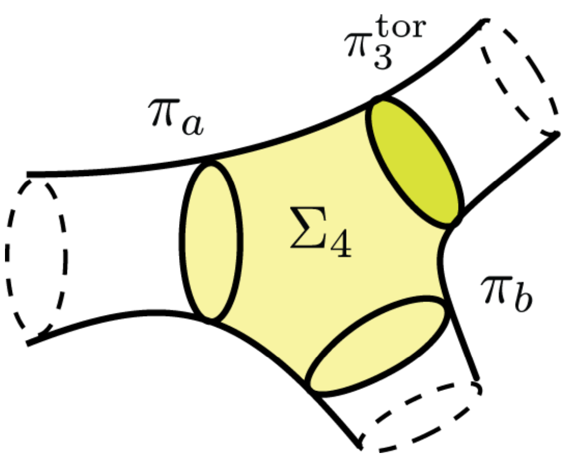
$$\begin{array}{ccccccc} & & & 1 & & & \\ & & 0 & & 0 & & \\ & 0 & & 11 & & 0 & \\ 1 & & 11 & & 11 & & 1 \\ & 0 & & 11 & & 0 & \\ & & 0 & & 0 & & \\ & & & 1 & & & \end{array}$$

$H_0(\mathcal{M}_6)$	$H_1(\mathcal{M}_6)$	$H_2(\mathcal{M}_6)$	$H_3(\mathcal{M}_6)$	$H_4(\mathcal{M}_6)$	$H_5(\mathcal{M}_6)$	$H_6(\mathcal{M}_6)$
$\mathbb{Z}$	$(\mathbb{Z}_2)^3$	$(\mathbb{Z})^{11} \oplus \mathbb{Z}_2$	$(\mathbb{Z})^{24} \oplus \mathbb{Z}_2$	$(\mathbb{Z})^{11} \oplus (\mathbb{Z}_2)^3$	0	$\mathbb{Z}$

Freely-acting $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2)$

RR U(1)'s allow for new phenomenological scenarios:

- Two stacks of fractional D6-branes which differ by $\pi_3^{\rm tor}$



Massless: $U(1)_Y \sim 2U(1)_a - 2U(1)_b + U(1)_{\rm RR}$

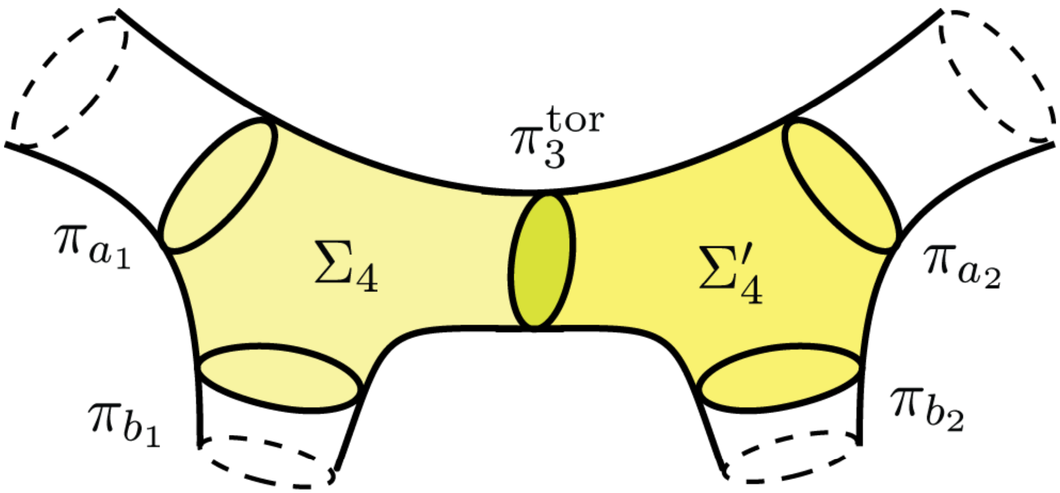
Massive: $U(1)_{G_1} \sim U(1)_a + U(1)_b$

$U(1)_{G_2} \sim U(1)_a - U(1)_b - 4U(1)_{\rm RR}$

$$f_{YG_2} = -\frac{4i}{27}\sqrt{\frac{10}{3}}(N^0 - T^{\hat{1}})$$

5. Some phenomenological implications

- Two mutualy hidden brane sectors which comunicate via RR photons



Massless:

$$U(1)_{Y_k} \sim 2U(1)_{a_k} - 2U(1)_{b_k} + U(1)_{\rm RR} \ , \quad k = 1, 2$$

Massive:

$$U(1)_{G_k} \sim U(1)_{a_k} + U(1)_{b_k}$$
$$U(1)_{G_3} \sim U(1)_{a_1} - U(1)_{b_1} + U(1)_{a_2} - U(1)_{b_2} - 4U(1)_{\rm RR}$$

$$f_{Y_1 Y_2} = -\frac{i}{80}(8T^{\hat{1}} - 9f_1 - 9f_2)$$

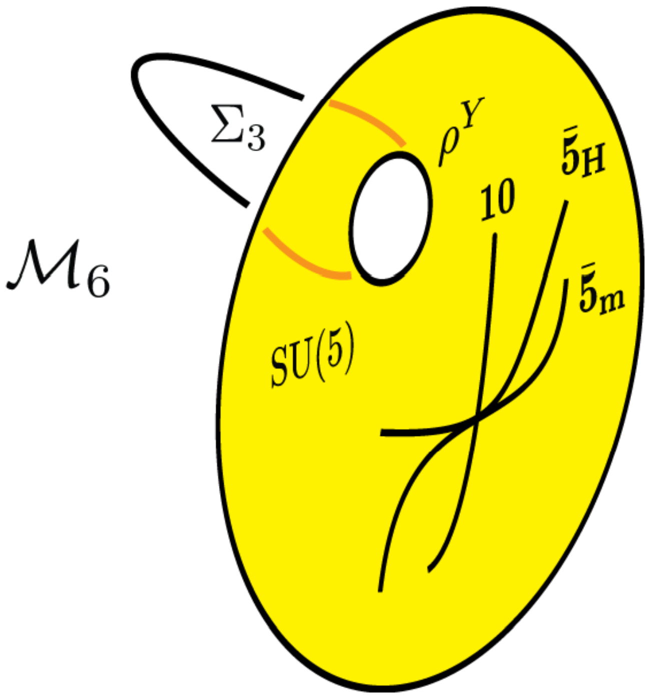
5. Some phenomenological implications

RR U(1)'s may also lead to new scenarios in the context of GUT models:

- Similar results for type IIB orientifolds with magnetized D7-branes (or their F-theory extension). RR photons arise from reduction of the RR 4-form on $H_3^+(\mathcal{M}_6, \mathbb{Z})$

- Let us consider SU(5) GUT models

[Beasley, Heckman, Vafa '08]
[Donagi, Wijnholt '08]



SU(5) 7-brane wraping 4-cycle S, matter fields localized at intersections...

Hypercharge flux breaking

$$SU(5) \to SU(3) \times SU(2) \times U(1)$$

$$\int_{\mathbb{R}^{1,3} \times S} C_4 \wedge F_Y \wedge \overline{F}_Y \ \to \ \int_{\mathbb{R}^{1,3}} C_2^Y \wedge F_Y$$

$$C_2^Y \ \equiv \int_S C_4 \wedge \overline{F}_Y \ = \ \int_{\rho^Y} C_4$$

5. Some phenomenological implications

- 2-cycle ρ^Y trivial in the CY_3 in order $U(1)_Y$ to remain massless.

- Thresholds (F^4) lead to wrong ordering of fine structure constants at M_s:

[Blumenhagen '08]

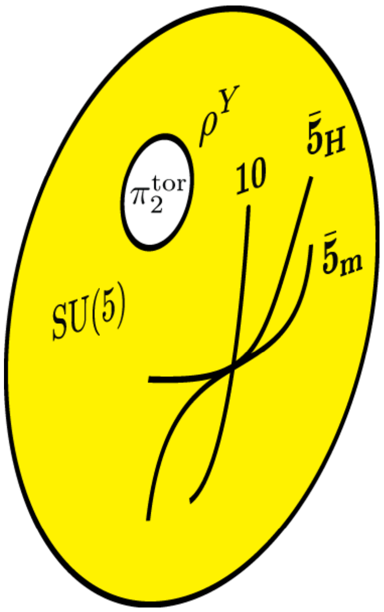
$$\frac{1}{\alpha_3} < \frac{1}{\alpha_1} < \frac{1}{\alpha_2}$$

The above condition can be relaxed. We can take ρ^Y to be trivial in $H_2^+(\mathcal{M}_6, \mathbb{R})$ but still non trivial in $H_2^+(\mathcal{M}_6, \mathbb{Z})$

I.e, ρ^Y can be a torsional 2-cycle of the CY_3.

Mixing of the "hypercharge" with a $U(1)_{RR}$

$$\mathcal{L} \supset -\frac{1}{2}\left(\mathrm{Re}(dT) + k_{\mathrm{RR}} A_{\mathrm{RR}} + \frac{5k_Y}{3} A_Y\right)^2$$



5. Some phenomenological implications

Mass eigenstates:

Massless: $A_1 = \cos(\theta)\tilde{A}_Y \; - \; \sin(\theta)\tilde{A}_{\rm RR}$

Massive: $A_X = \sin(\theta)\tilde{A}_Y \; + \; \cos(\theta)\tilde{A}_{\rm RR}$

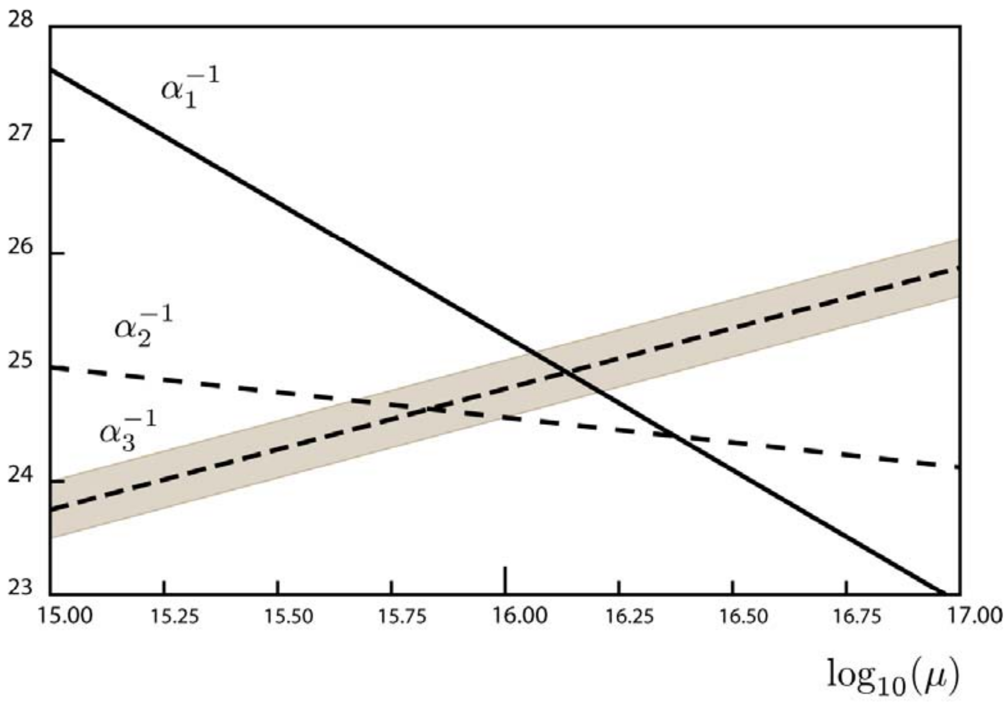
$$\sin(\theta) \equiv \frac{g_Y k_Y}{\sqrt{g_{\rm RR}^2 k_{\rm RR}^2 + g_Y^2 k_Y^2}}$$

The inverse fine structure constant of the massless U(1) is

$$\frac{1}{\alpha_1} = \frac{3}{5\alpha_{SU(5)}} + \frac{k_Y^2}{k_{\rm RR}^2 \alpha_{\rm RR}}$$

Could explain the known few percent discrepancy in MSSM gauge coupling unification.

Similar to [Tatar, Watari ’08]



6. The unified M-theory picture

M-theory provides a unifying picture for D-brane and RR U(1) gauge symmetries.

We consider M-theory on a G_2 manifold $\hat{\mathcal{M}}_7$ admitting at least one perturbative IIA CY_3 orientifold limit

$$\hat{\mathcal{M}}_7 \;\rightarrow\; (\mathcal{M}_6 \times S^1)/\hat{\sigma} \qquad\qquad \hat{\sigma} = (\sigma, -1)$$

b_2 massless U(1)'s and b_3 massless complex scalars:

$$A_3 = \mathrm{Re}(M^I)\phi_I + A^\alpha \wedge \omega_\alpha \qquad \Phi_3 = \mathrm{Im}(M^I)\phi_I \qquad \begin{array}{l} I = 1, \ldots, b_3(\hat{\mathcal{M}}_7) \\ \alpha = 1, \ldots, b_2(\hat{\mathcal{M}}_7) \end{array}$$

In the IIA perturbative limit they become the massless D6-brane and RR U(1)'s and the massless closed and open string moduli.

If $\hat{\mathcal{M}}_7$ admits several IIA perturbative limits, open / closed string dualities may exchange D6-brane and RR U(1)'s. [Kachru, McGreevy '01]

6. The unified M-theory picture

Gauge kinetic function described geometrically by the triple intersection numbers of $\hat{\mathcal{M}}_7$

[Papadopoulos, Townsend '99]

$$f_{\alpha\beta} = M^I \int_{\hat{\mathcal{M}}_7} \phi_I \wedge \omega_\alpha \wedge \omega_\beta$$

Massive U(1) gauge symmetries spontaneoulsy broken to discrete gauge symmetries arise from $\text{Tor } H_2(\hat{\mathcal{M}}_7, \mathbb{Z}) \simeq \text{Tor } H_4(\hat{\mathcal{M}}_7, \mathbb{Z})$

M2-branes wrapping torsional 2-cycles ⇨ 4d Aharanov-Bohm particles

M5-branes wrapping torsional 4-cycles ⇨ 4d Aharanov-Bohm strings

$$\hat{k}_\alpha{}^\beta \phi_\beta^{\text{tor}} = d\omega_\alpha^{\text{tor}} \qquad dA_3 = \left(\text{Re}(dM^\alpha) + \hat{k}^\alpha{}_\beta A^\beta\right) \wedge \phi_\alpha^{\text{tor}} + dA^\beta \wedge \omega_\beta^{\text{tor}}$$

In the IIA perturbative limit they become the massive D6-brane and RR U(1)'s.

Thus, in a general compactification massless U(1)'s and discrete gauge symmetries are both classified by $H_2(\hat{\mathcal{M}}_7, \mathbb{Z})$

7. Concluding remarks

• We have considered the interplay between open and closed string U(1) gauge symmetries.

• RR U(1)'s can play a prominent role. Mixing with the hypercharge can occur either via direct kinetic mixing or via the mass terms induced by Stückelberg couplings. Interesting phenomenological implications.

• We have provided a geometric description of mass mixing in terms of the torsional homology of the CY, and developped the right tools to compute the mixing parameters in specific models.

• As a byproduct , we have provided a stringy realization of discrete gauge symmetries and 4d A-B strings and particles in terms of the torsional homology. In particular $\mathrm{Tor}\, H_2(\hat{\mathcal{M}}_7, \mathbb{Z})$ should contain the MSSM discrete symmetries of any semi-realistic model.