Open string axions and the flavor problem

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Based on work with E. Perkins **arXiv:1003.4233, arXiv:1202.2073**

Motivation

- Dynamics of branes are interesting sources of models for particle physics: low energy field theory gives rise to “generic” looking chiral QFT.
- Candidate for Standard Model realization in string theory.
- Can string theory inspired mechanisms give rise to interesting low energy physics within effective field theory approach?
- Want to address flavor physics without discrete symmetry assumptions. Instead, use gauge theory constraints to get desired results: all global symmetries should be gauged.

Assumptions

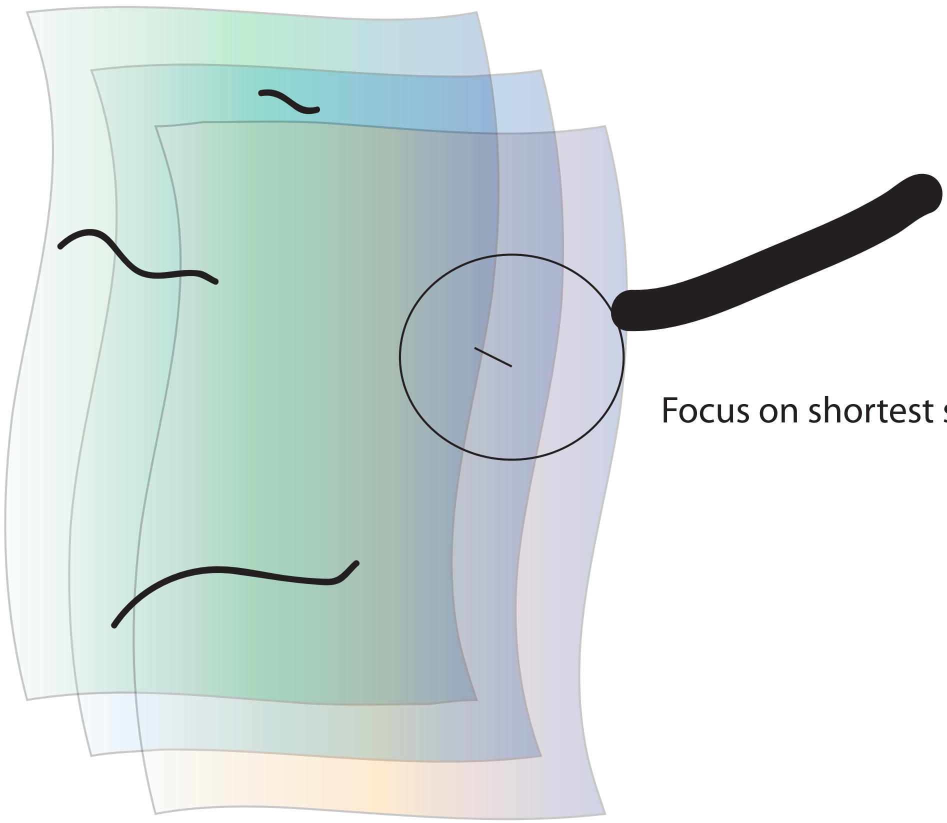
- Work in bottom-up approaches to phenomenology.
- This means things that can be obtained using just effective field theory plus some ‘stringy consistency’ constraints on couplings.
- Standard model parameters are input to theory: this lets us understand the new physics predictions.
- We check consistency of values of couplings with effective field theory reasoning: can use to rule out models where couplings are unnaturally large or small.

Outline

- Gauge groups and massless matter content.
- Stringy feature: Green-Schwarz mechanism in 4d and removal of U(1)'s.
- Adding flavor gauge symmetries and their breaking.
- Open string axions

D-brane effective field theory

D-branes can be stacked



D-brane dynamics contains massless gauge fields.

For N branes we get NxN matrices

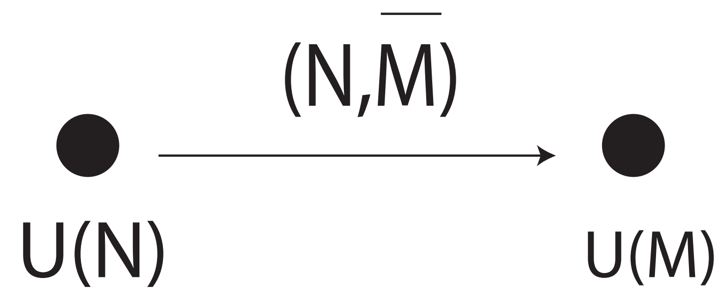
Leads to U(N), SO(N),Sp(N) gauge groups.

D-branes can intersect: open strings stretching between them have Chan-Paton factors.

These open strings carry bi-fundamental charges.

All of this is captured by quiver diagrams.

Nodes represent gauge groups
Arrows represent matter content



Fermions and bosons get each their own arrows (we don't impose SUSY). Chiral matter is allowed. In low energy limit, all spins are less than or equal to one: typical scenario for usual phenomenology.

Consistency conditions.

We need to satisfy tadpole constraints.
Gauss law for brane charges.

From the point of view of effective field theory, this is slightly stronger than anomaly cancellation. We will only impose the latter.

Green-Schwarz mechanism:

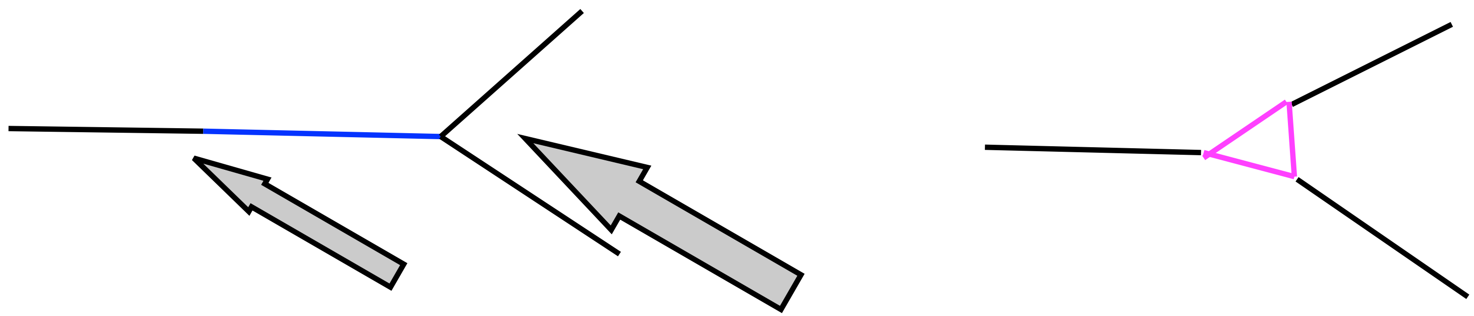
Anomaly cancellation only requires that the anomaly polynomial factorizes:

All $SU(N)^3$ cubic anomalies cancel

Mixed $U(1)G^2$ are allowed.

The Green-Schwarz mechanism cancels the mixed anomalies by using a massless closed string state.

In 4d this gives a Stueckelberg mass to the U(1)



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Investigated in detail by Kiritsis et al.

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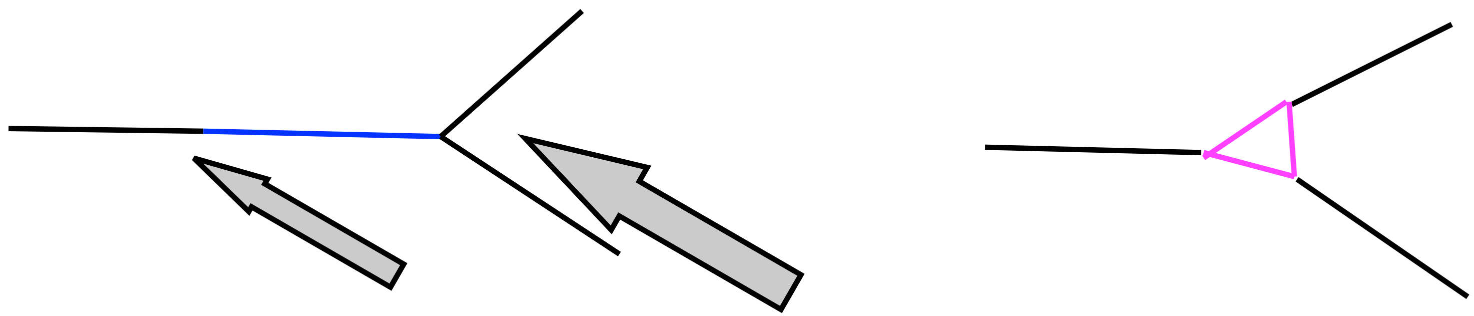

$g_o M_s \partial_\mu \phi A_\mu$ Axionic coupling

Mass is of order $g_s^{1/2} M_s$.

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These modes are essentially inevitable in D-brane constructions: the gauge group is U(N), never SU(N) alone.

The allowed coupling constants are those that have a well defined large N limit.

Tree level amplitudes are generated by discs: all coupling constants are “single trace operators” at the string scale.

MQSM

- Minimal model compatible with brane (at singularity) consistency conditions.
- Bottom up approach:use known physics to constrain model.
- Keep massive U(1)'s: Their mass is parametrically small compared to string scale.

$$g_s^{1/2} M_s$$

Gauge group:

U(3)x Sp(1)

U(3)xU(2)

Do not work

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Can't accommodate hypercharge assignments

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U(3)xSp(1)xU(1)

D.B. + Sam Pinansky **hep-th/0610104**

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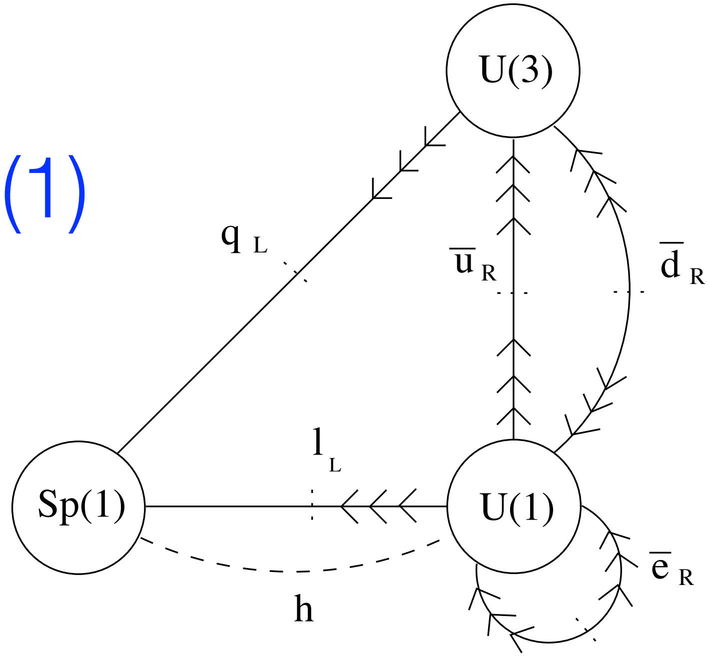

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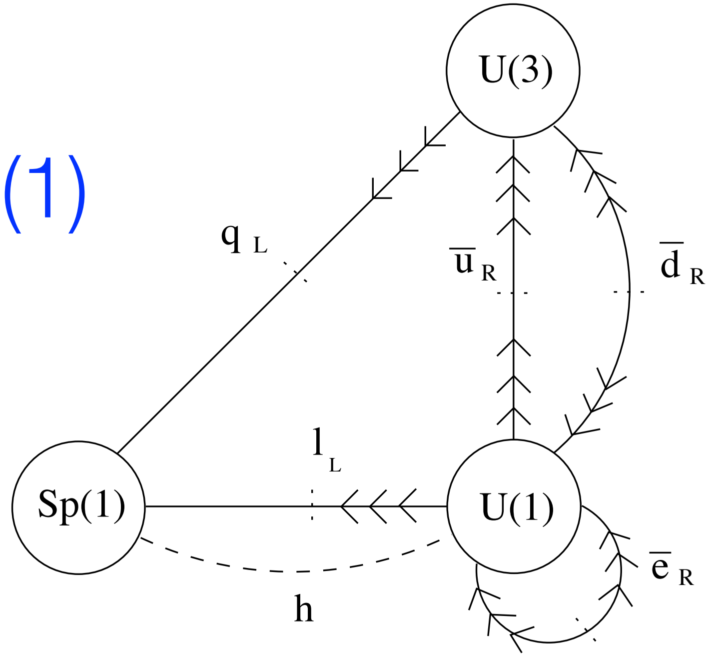

Completely flavor blind!

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Most general Yukawa coupling allowed by single traces

$$y^u_{ij} q^i_L \overline{u}^j_R h + y^d_{ij} q^i_L \overline{d}^j_R h^* + y^e_{ij} \ell^i \overline{e}^j_R h^* + \mathrm{h.c.}.$$

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All Yukawa couplings of standard model are allowed by tree level interactions. The model predicts a single heavy Z' with all its coupling constants fixed except mass.

Adding Flavor symmetries

- All global symmetries in gravity should be gauged (folk theorem, also based on black hole physics).

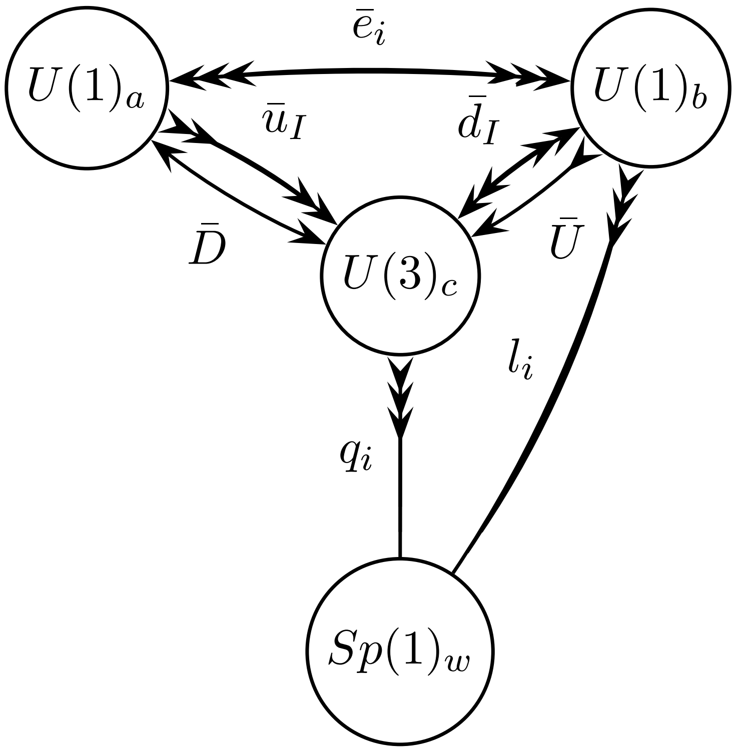
- In particular, flavor symmetries if not discrete, should be gauged (like Frogatt-Nielsen mechanism)

- To do this with D-branes, we need to take SM quiver and add branes: distinguishes families and gives rise to possibility of explaining flavor hierarchies.

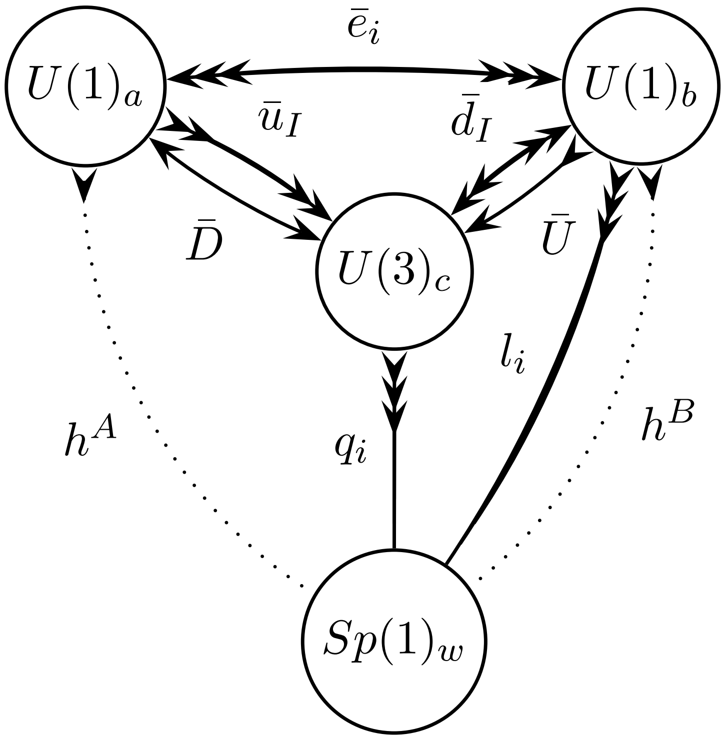
- We want to retain minimality assumptions: introduce as few particles as possible: keep only one Higgs doublet.

Simplest quiver: fermion assignment

$$U(3) \times SP(1) \times U(1) \times U(1)$$

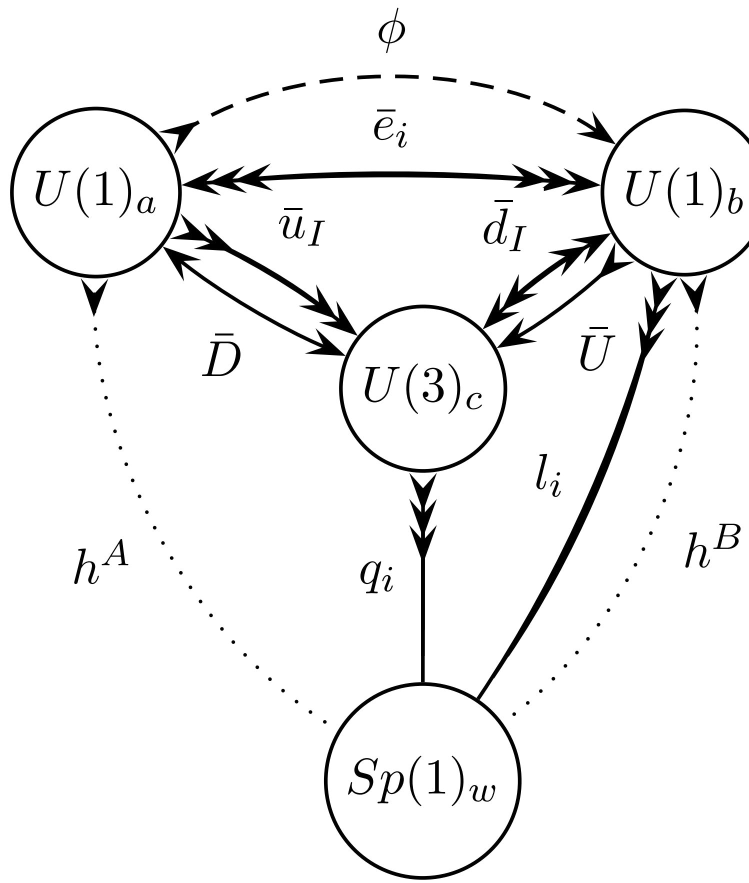


Two places where the Higgs can go



Notice that with this quiver some fermion masses are forbidden: need to add particles to produce SM masses at tree level.

Add complex scalar field to communicate mass generation via its vev.



This is basically the Froggatt-Nielsen mechanism: we get a precise set of charges for FN field from quiver.

If you prefer table of charges

	$\bar{u}_R^{1,2}$	$\bar{d}_R^1$	$\bar{u}_R^3$	$\bar{d}_R^{2,3}$	e_L	$\bar{e}_R$	ϕ	$h^{A,B}$
$U(1)_a$	+1	-1	0	0	0	-1	+1	+1, 0
$U(1)_b$	0	0	+1	-1	+1	-1	-1	0, +1

Two models distinguished by Higgs location.

Analysis

If we break FN symmetry, some standard model operators are suppressed by mass ratios.

$$\left(\frac{\langle\phi\rangle}{M}\right)^n \mathcal{O}_{SM}$$

$$\left(\frac{\langle\phi\rangle}{M}\right) \simeq f\left(\frac{m_i}{m_j}\right)$$

Still need to determine M

Key: use the dimension 5 operators that we know don't vanish in the standard model, neutrino masses.

Analysis of couplings (model A)

Dimension 4 couplings	$h^\dagger q\bar{u}_I + hq\bar{D} + hl\bar{e}$
High dimension couplings	$\phi h^\dagger q\bar{U} + \phi^\dagger hq\bar{d}_I + (\phi h^\dagger l)^2$
$\langle\phi\rangle \simeq \frac{m_s}{m_t}\frac{m_s^2}{m_{\nu_\tau}}$	10^3 GeV
$M \simeq \frac{m_s^2}{m_{\nu_\tau}}$	10^6 GeV

In this model neutrino masses are dimension 7 operator in full theory.

Analysis of couplings, model B

Dimension 4 couplings	$h^\dagger q\bar{U} + hq\bar{d}_I$
High dimension couplings	$\phi^\dagger h^\dagger q\bar{u}_I + \phi hq\bar{D} + \phi hl\bar{e} + (h^\dagger l)^2$
$\langle\phi\rangle \simeq \frac{m_c}{m_t}\frac{m_t^2}{m_{\nu_\tau}}$	10^{11} GeV
$M \simeq \frac{m_t^2}{m_{\nu_\tau}}$	10^{13} GeV

Neutrino masses are dimension 5 in this model: makes Frogatt-Nielsen scale higher.

Anomalies

Only U(1) of hypercharge is anomaly free.

The other two U(1)'s have mixed anomalies that need to be cancelled via Green-Schwarz: they become massive Z'

We can integrate them out!

But there is more

The global part of the U(1) Frogatt Nielsen survives as a perturbative symmetry of the low energy theory.

Ibañez-Quevedo mechanism.

This means that the phase of the field ϕ acts as a Goldstone boson.

However, symmetry is anomalous, so it's only a pseudo-Goldstone boson

Candidate axion!

Coming from open string degrees of freedom.

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Similar possibility noticed by Kiritsis et al.
Their axions where problematic (not invisible: axi-Higgs)

Vev of ϕ is essentially the axion decay constant.

Model A is ruled out by data (lower sill of axion window determined by SN1987a data- Supernovae cooling)

$$10^{13} GeV > f_a > 10^8 - 10^9 GeV$$

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Model B is just right

Bonus:

All axion couplings can be determined from high energy and followed all the way to the QCD scale. The couplings depend only on anomalies, plus (a small) mixing with closed string axion.

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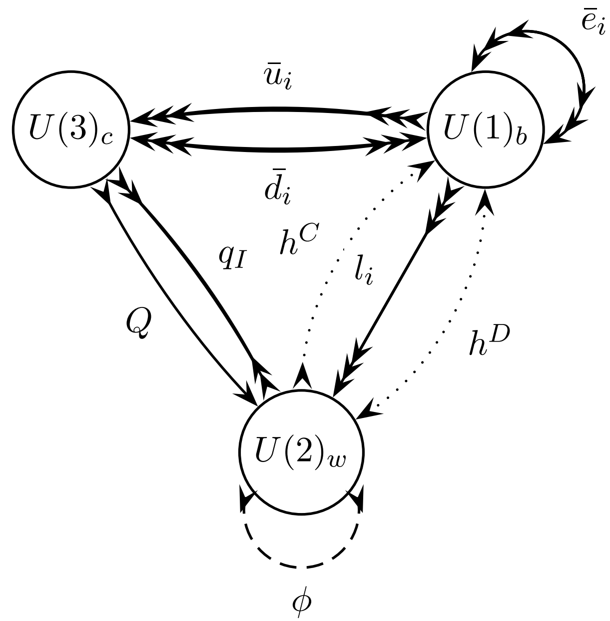
Even if mixing with closed string axion is large, the bound on axion decay constant is robust: we can not make it larger.

Can also do three stack models



Upon inspection of details of masses they seem to be wrong, or axion decay constant bad (again from neutrinos having high dimension mass operators)

Problems with all these models

- All quark doublets are identical: no information on mixing angles between generations (no CKM structure)

- Ratios between masses still require some fine tunings.

Proposed fix for CKM: ask quark doublets to attach to different branes. This forces much larger extension of gauge group.

We probably need

$$U(3) \times U(3) \times \ldots$$

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OR

More elaborate?

Such models would deconstruct an extra dimension: indicate that 'higher dimensions' are in some sense required always.

(When we started this is what we were trying to avoid)

Conclusion

- Bottom up approaches can lead to interesting mass textures from simple D-brane extensions of standard model.
- Frogatt-Nielsen+Green-Schwarz+Ibañez-Quevedo = Models with open string axions (could be very generic).
- Axion decay constant can be very low or intermediate (depends on details): many can be ruled out by current observations.
- Current data constraints these models a lot, and might be observed in current experiments (CAST, or ADMX), which are closing in on the lower sill of axion window.

Outlook

- Understand deconstruction models.
- Explore SUSY versions of this setup.
- Issues: saxion, need for more than one FN field, large list of extra parameters, SUSY breaking, issues with mu terms, axion-Higgs mixing, etc.