Stringy Quivers: Constraints on Chiral Matter and Systematic Phenomenological Searches

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Mostly based on:
1108.tonight with M. Cvetič and P. Langacker

University of Pennsylvania

Also based on:
0905.3379 with M. Cvetič and R. Richter
0909.4292 with M. Cvetič and R. Richter
0910.2239 with M. Cvetič and R. Richter
1001.3148 with M. Cvetič, P. Langacker, and R. Richter
1006.3341 with M. Cvetič and P. Langacker

Motivation (broadly)

String Theory:

* is a consistent UV complete theory with QG.
* can contain low energy effective theories which look like the SM.

Question:

if it described the real world, how would we know?
More precisely, how would we distinguish from FT?

One Answer: (best in theory, worst in practice)

Study physics ST gives you that FT doesn't.

⇨ requires energy scales (typically) much too high.

Motivation (this talk)

Another answer: (okay in theory, good in practice)

* study string-motivated FT's.
* are their phenomenological properties better?

  (will give a prominent class of examples, complete with pheno.)
* not ideal: could address in ST or FT.

One last answer: (good in theory, good in practice)

* study string constraints not present in FT.

  (i.e. not all EFT's are consistent with string constraints. Can we learn something?)

this talk will utilize both of these answers.

affects low energy physics:

gauge sym., chiral matter, superpotential, etc.

Outline

Motivation

String-Motivated “Augmented” Field Theories

review quivers with ``anomalous” U(1)’s (type IIa, IIb, and others)

pheno of U(1)’s and non-perturbative effects

Implications of String Constraints

statement of constraints necessary for tadpole cancellation and massless Y boson

interesting examples of their importance

systematic studies of ``preferred” matter and Zprime beyond the standard model

Conclusion

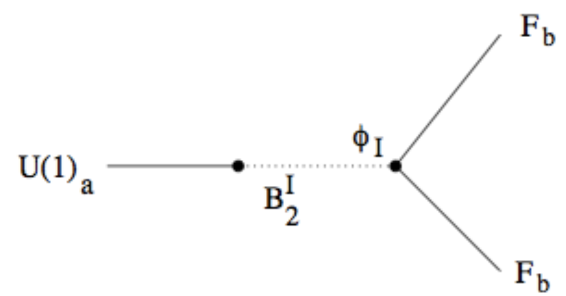
Stringy Quivers, the Basics

FT from ST often have: (type II intersecting branes, type I, some het)

- * SM-like gauge symmetry and chiral matter
- * ``anomalous" U(1)'s (can give interesting pheno, couplings, etc)
- * Chern-Simons terms for anomaly cancellation

$$\int_{\mathbb{R}^{3,1}} B \wedge F$$

$$\int_{\mathbb{R}^{3,1}} \phi \; Tr(F \wedge F)$$



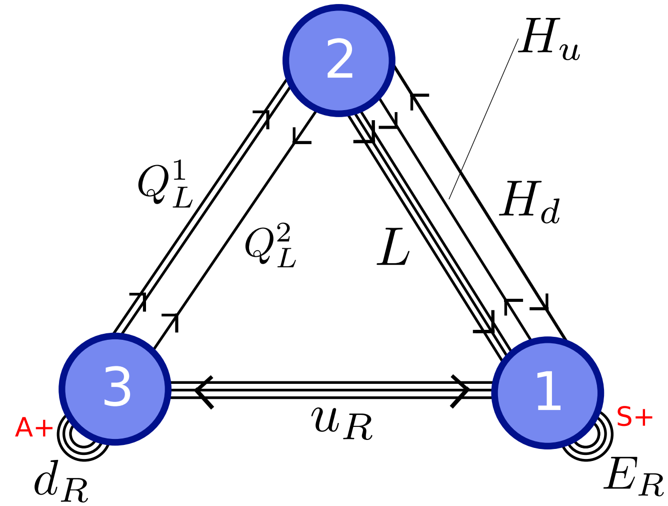
- * important consistency conditions (will discuss!)

could discuss purely as "augmented" field theory but strongly motivated by string theory.

These FT's as Quivers

Can represent as a quiver:

node with #:	U(#) gauge factor
arrow out:	fund. of node
arrow in:	antifund. of node
self-edges:	antisym. or sym. products



Y is linear comb.

e.g. $$Q_Y = \frac{1}{6}U(1)_3 + \frac{1}{2}U(1)_1$$

which is known as a "hypercharge embedding"

Quiver above is a 3-node quiver.
We'll also discuss 4-node and 5-node with 1 or 2 extra U(1) nodes.

Physics of Anomalous U(1)'s

anomalous U(1)'s affect pheno:

* same SM rep, different U(1) charges
  (natural lepton, down-Higgs distinction)
  (non-trivial family structure. i.e. diff U(1) charges)
* selection rules on superpotential
  (some couplings forbidden in string perturbation theory)
* there can be non-pert. D-inst. corrections
  (must have for Majorana neutrino mass, 10 10 5)
  (can have realistic MSSM Yukawa's, solve μ-problem, LH_uN_R correct scale)
  (many other interesting possibilities)
  (note: couplings are suppressed. U(1) charge of couplings "link" scales)
  e.g. MSSM Yukawas, proton decay operators might be gen'd
  by the same non-perturbative effect, therefore at same scale.

D-instantons
[Blumenhagen, Cvetic, Weigand]
[Ibanez, Uranga]
[Florea, Kachru, McGreevy, Saulina]

Systematic Quiver Pheno: Results

construct all consistent quivers in a given class
then study pheno at level of W couplings

Realistic Yukawa Structures: [Cvetic, Halverson, Richter] x 3

can have semi-realistic Yukawa's w neutrino mechanism, avoiding R-parity violating couplings and allowing **μ** of correct order. Can have realistic mass hierarchies while avoid problems, but 5-node quivers. Must be careful with dimension 5 proton decay operators.

Non-perturbative Neutrino Mass: [Cvetic, Halverson, Langacker, Richter]

directly generate the Weinberg operator by a D-instanton. Low string scale?

Singlet-Extended Models: [Cvetic, Halverson, Langacker]

can get dynamical **μ**-term via singlet VEV. Could have polynomial f(S) in superpotential without spoiling other physics. i.e. nMSSM, S^2, NMSSM

see also: [Anastasopoulos, Kiritsis, Lionetto]
[Anastasopoulos, Leontaris, Richter, Schellekens]

Example List of Semi-Realistic Quivers

Solution #	q_L		d_R			u_R		L			E_R			N_R				H_u				H_d
	(a,b)	$(a,\bar{b})$	$(\bar{a},c)$	$(\bar{a},\bar{d})$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}_a$	$(\bar{a},\bar{c})$	$(\bar{a},d)$	$(b,\bar{c})$	(b,d)	$(\bar{b},d)$	$(c,\bar{d})$	$\square\square_c$	$\overline{\square\square}_d$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}_b$	$\overline{\begin{smallmatrix}\square\\\square\end{smallmatrix}}_b$	(c,d)	$(\bar{c},\bar{d})$	(b,c)	$(\bar{b},c)$	$(b,\bar{d})$	$(\bar{b},\bar{d})$	$(\bar{b},\bar{c})$
$1^{\dagger}$	3	0	3	0	0	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
2	3	0	3	0	0	0	3	0	0	3	1	0	2	2	0	1	0	0	0	0	1	1
$3^{\dagger}$	3	0	2	0	1	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
4	3	0	2	0	1	0	3	0	0	3	1	0	2	2	0	1	0	0	0	0	1	1
$5^{\dagger}$	3	0	1	0	2	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
6	3	0	1	0	2	0	3	0	0	3	1	0	2	2	0	1	0	0	0	0	1	1
$7^{\dagger}$	3	0	0	0	3	0	3	0	0	3	0	0	3	2	0	0	1	0	0	0	1	1
$8^{\dagger}$	3	0	0	0	3	0	3	0	0	3	0	0	3	3	0	0	0	1	0	0	0	1
9	3	0	0	0	3	0	3	0	0	3	1	0	2	2	0	1	0	0	0	0	1	1
10	3	0	3	0	0	2	1	0	0	3	2	1	0	2	0	1	0	0	0	0	1	1
11	3	0	3	0	0	2	1	0	0	3	0	2	1	2	0	1	0	0	0	0	1	1
12	3	0	3	0	0	3	0	0	0	3	2	1	0	2	0	0	1	0	1	0	0	1
13	3	0	3	0	0	3	0	0	0	3	0	2	1	2	0	0	1	0	1	0	0	1
14	3	0	3	0	0	3	0	0	0	3	1	2	0	2	0	1	0	0	1	0	0	1
$15^{\clubsuit}$	2	1	3	0	0	1	2	0	0	3	0	0	3	0	0	0	3	1	0	0	0	1
$16^{\clubsuit\bullet}$	2	1	3	0	0	1	2	0	0	3	3	0	0	0	0	3	0	1	0	0	0	1
$17^{\clubsuit\bullet}$	2	1	3	0	0	1	2	0	0	3	1	1	1	0	0	3	0	1	0	0	0	1
$18^{\clubsuit\dagger}$	2	1	3	0	0	3	0	0	0	3	3	0	0	0	0	0	3	1	0	0	0	1
$19^{\clubsuit}$	2	1	3	0	0	3	0	0	0	3	1	1	1	0	0	0	3	1	0	0	0	1
$20^{\clubsuit\bullet}$	2	1	3	0	0	3	0	0	0	3	0	3	0	0	0	3	0	1	0	0	0	1
$21^{\clubsuit}$	2	1	3	0	0	3	0	0	2	1	2	1	0	2	0	0	1	1	0	0	0	1
$22^{\clubsuit}$	2	1	3	0	0	3	0	0	2	1	1	2	0	2	0	1	0	1	0	0	0	1
$23^{\clubsuit}$	1	2	3	0	0	3	0	0	1	2	2	1	0	0	2	0	1	1	0	0	0	1
$24^{\clubsuit\dagger}$	1	2	3	0	0	3	0	0	3	0	3	0	0	0	0	0	3	1	0	0	0	1
$25^{\clubsuit}$	1	2	3	0	0	3	0	0	3	0	1	1	1	0	0	0	3	1	0	0	0	1
$26^{\heartsuit}$	0	3	0	3	0	0	3	3	0	0	2	0	1	0	3	0	0	0	0	1	0	1
$27^{\heartsuit}$	0	3	0	3	0	0	3	3	0	0	0	1	2	0	3	0	0	0	0	1	0	1
$28^{\dagger}$	0	3	0	0	3	0	3	0	3	0	0	0	3	0	3	0	0	1	0	0	0	1
$29^{\dagger}$	0	3	0	0	3	0	3	1	2	0	1	0	2	0	3	0	0	0	0	1	0	1
30	0	3	0	0	3	0	3	3	0	0	2	0	1	0	3	0	0	0	0	1	0	1
31	0	3	0	0	3	0	3	3	0	0	0	1	2	0	3	0	0	0	0	1	0	1
32	0	3	0	3	0	1	2	3	0	0	3	0	0	0	3	0	0	1	0	0	0	1
33	0	3	0	3	0	1	2	3	0	0	1	1	1	0	3	0	0	1	0	0	0	1
$34^{\dagger}$	0	3	0	0	3	1	2	1	2	0	2	0	1	0	3	0	0	1	0	0	0	1
$35^{\dagger}$	0	3	0	0	3	1	2	1	2	0	0	1	2	0	3	0	0	1	0	0	0	1
36	0	3	0	0	3	1	2	3	0	0	3	0	0	0	3	0	0	1	0	0	0	1
37	0	3	0	0	3	1	2	3	0	0	1	1	1	0	3	0	0	1	0	0	0	1
38	0	3	0	0	3	2	1	0	3	0	3	0	0	0	3	0	0	1	0	0	0	1
39	0	3	0	0	3	2	1	0	3	0	1	1	1	0	3	0	0	1	0	0	0	1
$40^{\dagger}$	0	3	0	0	3	2	1	2	1	0	2	1	0	0	3	0	0	1	0	0	0	1
$41^{\dagger}$	0	3	0	0	3	2	1	2	1	0	0	2	1	0	3	0	0	1	0	0	0	1
$42^{\dagger}$	0	3	0	3	0	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
$43^{\dagger}$	0	3	0	2	1	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
$44^{\dagger}$	0	3	0	1	2	3	0	3	0	0	0	3	0	0	3	0	0	1	0	0	0	1
45	0	3	0	0	3	3	0	1	2	0	1	2	0	0	3	0	0	1	0	0	0	1

Revisiting our Second Answer

Question:

if it described the real world, how would we know?

More precisely, how would we distinguish from FT?

Second Answer: (okay in theory, good in practice)

* study string-motivated FT's.
* are their phenomenological properties better?

(“better” is always a loaded word. but in class we discussed, FT augmentations offered by string theory can give natural explanations for observed phenomena not explained in SM).

* good, but still not ideal:

could address in ST or FT.

Another Approach

the discussed systematic work constructed all quivers with a given spectrum (MSSM, e.g.), kept only those which might be consistent.

i.e. not all MSSM quivers are consistent.

(generically they violate constraints on chiral matter, to be discussed shortly)

point: more constraints than in standard FT.

(What are they and what do they tell us physically?)

will show: some are stringy. i.e. apparently no FT analog . . .

Constraints on Chiral Matter 1

necessary for tadpole cancellation

(cancellation of D-brane charge on compact internal space via Gauss' law)

$$N_a \geq 2: \qquad \#a - \#\bar{a} + (N_a + 4)\,(\#\square\!\square_a - \#\overline{\square\!\square}_a) + (N_a - 4)\,(\#\begin{smallmatrix}\square\\\square\end{smallmatrix}_a - \#\overline{\begin{smallmatrix}\square\\\square\end{smallmatrix}}_a) = 0$$

$$N_a = 1: \qquad \#a - \#\bar{a} + (N_a + 4)\,(\#\square\!\square_a - \#\overline{\square\!\square}_a) = 0 \ \bmod\ 3, \qquad \text{(A.3)}$$

must be satisfied by each $U(N_a)$ gauge symmetry, e.g. on stack of D6-branes.

for $N_a \geq 3$ these are constraints for absence of

$SU(N_a)^3$ triangle anomalies.

for $N_a = 2, 1$ there are no such anomalies.

but these are still necessary for string consistency.

refer to non-zero LHS as "T"-charge

Constraints on Chiral Matter 2

recall theory has Chern-Simons couplings which participate in anomaly cancellation.

fact: couplings of the form $\int_{\mathbb{R}^{3,1}} B \wedge F$

give a Stuckelberg mass to U(1) gauge bosons

necessary for massless U(1) boson $\quad U(1)_G = \sum_x q_x U(1)_x$

$$-q_a N_a \left(\#\Box\!\Box_a - \#\overline{\Box\!\Box}_a + \#\substack{\Box\\\Box}_a - \#\overline{\substack{\Box\\\Box}}_a\right) + \sum_{x \neq a} q_x N_x \left(\#(a,\bar{x}) - \#(a,x)\right) = 0 \qquad \text{(A.5)}$$

$$-q_a \frac{\#(a) - \#(\bar{a}) + 8(\#\Box\!\Box_a) - \#\overline{\Box\!\Box}_a)}{3} + \sum_{x \neq a} q_x N_x \left(\#(a,\bar{x}) - \#(a,x)\right) = 0 \qquad \text{(A.6)} \qquad N_a = 1$$

require hypercharge to be such a linear combination

refer to LHS as “M”-charge

Illustrative Examples $U(3)_a \times U(2)_b \times U(1)_c \qquad U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c$

[Cvetic, J.H., Langacker]

Consider a quiver: $(c, \overline{d})$ x 3 3 MSSM singlets

from FT point of view: quiver is boring / mundane

could add as right-handed neutrino sector to a consistent MSSM quiver

from ST point of view: the hypercharge boson must get a mass since

$$M_c = 3 \qquad M_d = -3$$

paper has a similar example for a standard model vector pair

Consider a quiver:

$$q_L : (a, \overline{b})_{1,-1,0} \qquad u_L^c : (\overline{a}, \overline{c})_{-1,0,-1} \qquad d_L^c : (\overline{a}, c)_{-1,0,1}$$

$$L : (\overline{b}, \overline{c})_{0,-1,-1} \qquad e_L^c : (\square\square_c)_{0,0,2},$$

x 3

$H_u : (b, c) \qquad H_d : (\overline{b}, \overline{c})$ MSSM spectrum

quiver is anomaly-free (perhaps w/ CS terms)

no known field-theoretic pathology

not embeddable in a string compactification since $T_b = -12$

This last example is quite general!

3-Node Quivers with $U(3)_a \times U(2)_b \times U(1)_c$ $\quad U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c$

[Cvetic, J.H., Langacker]

straightforward exercise:

write down all 3-node quivers with MSSM spectrum and Madrid embedding

they have

$$T_a = 0 \qquad T_b = \pm 2n \qquad T_c = 0 \bmod 3 \qquad \text{with } n \in \{0, \ldots, 7\}$$

and have zero M-charge.

suggestive of matter beyond SM:

need matter additions to have T-charge on b-node.

most common possibilities include:

- doublet pairs (quasichiral for non-zero Tb, pairs so no T-charge on others nodes)
- MSSM singlets as antisymmetrics representations
- SU(2) triplets with hypercharge zero

these are string theoretic preferences

the Tb condition was precisely the one argued to be string theoretic

and it prefers some matter fields over others

Systematic 3-Node and 4-Node Analyses

[Cvetic, J.H., Langacker]

"listen" to constraints regarding matter BSM

only pheno input: (really want the constraints to do the work)

quiver contains MSSM. Hypercharge is massless.

rules of systematics:

1) construct all MSSM quivers in 8 Y embeddings.

nearly all are inconsistent

2) systematically add up to 5 matter fields.

exclude vector pairs:

T=0, M=0. generically high mass, quivers can map to each other after integrating out heavy vector pairs.

most general additions allowed by the quiver. (bifund, sym, antisym)

3) if constraints satisfied, quiver is allowed.

Matter additions . . . minimal pheno input

[Cvetic, J.H., Langacker]

SM Rep	Total Multiplicity	Int. El.	4^{th} Gen. Removed	Shifted 4^{th} Gen. Also Removed
$(\mathbf{1},\mathbf{1})_0$	174276	173578	173578	173578
$(\mathbf{1},\mathbf{3})_0$	48291	48083	48083	48083
$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	39600	39560	38814	38814
$(\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	38854	38814	38814	38814
$(\overline{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}$	25029	25007	24261	24241
$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	24299	24277	24277	24241
$(\mathbf{1},\mathbf{1})_1$	15232	15228	14482	14482
$(\mathbf{1},\mathbf{1})_{-1}$	14486	14482	14482	14482
$(\overline{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}}$	3501	3501	2755	2755
$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	2755	2755	2755	2755
$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	1784	1784	1038	1038
$(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	1038	1038	1038	1038
$(\mathbf{1},\mathbf{2})_0$	852	0	0	0
$(\mathbf{1},\mathbf{2})_{\frac{3}{2}}$	220	220	220	184
$(\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$	204	204	204	184
$(\mathbf{1},\mathbf{1})_{\frac{1}{2}}$	152	0	0	0
$(\mathbf{1},\mathbf{1})_{-\frac{1}{2}}$	152	0	0	0
$(\mathbf{3},\mathbf{1})_{\frac{1}{6}}$	124	0	0	0
$(\overline{\mathbf{3}},\mathbf{1})_{-\frac{1}{6}}$	124	0	0	0
$(\mathbf{3},\mathbf{1})_{-\frac{4}{3}}$	36	36	36	0
$(\mathbf{1},\mathbf{3})_{-1}$	36	36	36	0
$(\overline{\mathbf{3}},\mathbf{2})_{\frac{5}{6}}$	36	36	36	0
$(\overline{\mathbf{3}},\mathbf{1})_{\frac{4}{3}}$	20	20	20	0
$(\mathbf{1},\mathbf{3})_1$	20	20	20	0
$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	20	20	20	0

$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$ $(\overline{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}$ $(\overline{\mathbf{3}},\mathbf{1})_{\frac{4}{3}}$ $(\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$ $(\mathbf{1},\mathbf{3})_1$

Observations:

* singlets most common. have anomalous U(1) charge.
* triplets w Y=0 common
* quasichiral Higgs/lepton pairs
* down-type quark anti-quark pairs favored over up-type.

After Cuts:

* singlets, triplets still dominate
* many quasichiral pairs. mass terms not present in string perturbation theory. Can be generated with exponential suppression via D-instantons.

Other Aspects Studied . . . Pheno Cuts

[Cvetic, J.H., Langacker]

Generic Quivers:

for each hypercharge embedding, counts of quivers with distinct down-Higgs candidates, as well as counts of singlets which couple as SH_uH_d or LH_uN_r.

Hypercharge	Multiplicity of Quivers					
	Total	Int. El.	H_d Candidate	No 4th Gen	$S_\mu H_u H_d$	$\nu_L^c H_u L$
$(-\frac{1}{3},-\frac{1}{2},0)$	41	41	0	0	0	0
$(\frac{1}{6},0,\frac{1}{2})$	105	105	0	0	0	0
$(-\frac{1}{3},-\frac{1}{2},0,0)$	6974	6974	4954	4938	1824	2066
$(-\frac{1}{3},-\frac{1}{2},0,\frac{1}{2})$	70	0	0	0	0	0
$(-\frac{1}{3},-\frac{1}{2},0,1)$	4176	4176	1842	1792	0	80
$(\frac{1}{6},0,\frac{1}{2},0)$	480	16	0	0	0	0
$(\frac{1}{6},0,\frac{1}{2},\frac{1}{2})$	77853	77853	54119	53654	16754	15524
$(\frac{1}{6},0,\frac{1}{2},\frac{3}{2})$	265	265	0	0	0	0

Zprime Quivers:

sometimes another linear combination is left massless. U(1)' symmetry.

does not require low string scale, like some other attempts in the literature.

about 70% of the quivers are family non-universal.

Hypercharge	Multiplicity of Quivers				
	$U(1)'$	H_d Candidate	Fam. Univ	$S_\mu H_u H_d$	$LH_u\nu_L^c$
$(-\frac{1}{3},-\frac{1}{2},0)$	0	0	0	0	0
$(\frac{1}{6},0,\frac{1}{2})$	1	0	0	0	0
$(-\frac{1}{3},-\frac{1}{2},0,0)$	198	146	56	70	94
$(-\frac{1}{3},-\frac{1}{2},0,\frac{1}{2})$	0	0	0	0	0
$(-\frac{1}{3},-\frac{1}{2},0,1)$	78	16	10	0	5
$(\frac{1}{6},0,\frac{1}{2},0)$	0	0	0	0	0
$(\frac{1}{6},0,\frac{1}{2},\frac{1}{2})$	1803	1466	629	610	600
$(\frac{1}{6},0,\frac{1}{2},\frac{3}{2})$	82	0	0	0	0

see paper for more physics.

Conclusions

String-motivated EFT: (natural ingredients --> nice pheno details)

examples we consider have anomalous U(1)'s and Chern-Simons terms.
(type IIa intersecting braneworlds and related parts of the landscape)
non-perturbative effects + structure of U(1)s have strong implications for pheno.
* presence of anomalous U(1)'s gives natural explanation for observed family str.
* can get realistic Yukawas, μ, neutrinos (multiple mechanisms), much more . . .

String constraints on chiral matter:

more constraining than anomalies / FT const.

constraints prefer some matter/physics over others. (singlets, triplets, quasichiral pairs, family non-univ Z', etc.)

non-trivial patch of landscape. (not just IIa)

Future work?

do constraints appear in F-theory or M-theory? (Dudas-Palti relations?)
what else can we learn about physics from these constraints?