Physics Beyond the MSSM from the Top-Down

Universidad de Granada

- CERN, Barcelona, Penn, Granada
- The standard paradigm
- Uniqueness or environment
- The string landscape
- Extended MSSM quivers
- String remnants

CERN, Barcelona, Penn, Granada

PHYSICAL REVIEW D
PARTICLES AND FIELDS

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RAPID COMMUNICATIONS

Rapid Communications are intended for important new results which deserve accelerated publication, and are therefore given priority in editorial processing and production. A Rapid Communication in **Physical Review D** *should be no longer than five printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but because of the accelerated schedule, publication is generally not delayed for receipt of corrections unless requested by the author.*

Determination of Z' gauge couplings to quarks and leptons at future hadron colliders

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(Received 25 March 1993)

We point out that at future hadron colliders the ratio of cross sections for $pp \to Z' \to l^+l^-$ in two rapidity bins is a useful probe of the relative couplings of the Z' to u and d quarks. Combined with the forward-backward asymmetry, the rare decay modes $Z' \to Wl\nu_l$, and three associated productions $pp \to Z'V$ ($V = Z, W, \gamma$), and assuming interfamily universality, small Z-Z' mixing, and the Z' charge commuting with the $SU(2)_L$ generators, three out of four normalized couplings could be extracted. An analysis of the statistical uncertainties expected for the above probes at the CERN LHC for typical models with $M_{Z'} \simeq 1$ TeV shows that one lepton coupling and two combinations of quark couplings could be determined to around 5%, 20%, and 30%, respectively. This allows for a clear distinction between models.

PACS number(s): 12.15.Cc, 13.38.+c, 13.85.Qk, 14.80.Er

PHYSICAL REVIEW D — VOLUME 52, NUMBER 1 — 1 JULY 1995

Reconstruction of the extended gauge structure from Z' observables at future colliders

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(Received 27 January 1995)

The discovery of a new neutral gauge boson Z' with a mass in the TeV region would allow for the determination of gauge couplings of the Z' to ordinary quarks and leptons in a model-independent way. We show that these couplings in turn would allow us to determine the nature of the extended gauge structure. As a prime example we study the E_6 group. In this case two discrete constraints on experimentally determined couplings have to be satisfied. If so, the couplings would then uniquely determine the two parameters $\tan\beta$ and δ which fully specify the nature of the Z' within E_6. If the Z' is part of the E_6 gauge structure, then for $M_{Z'} = 1$ TeV $\tan\beta$ and δ could be determined to around 10% at the future colliders. The NLC provides a unique determination of the two constraints as well as of $\tan\beta$ and δ, though with slightly larger error bars than at the CERN LHC. On the other hand, since the LHC primarily determines three out of four normalized couplings, it provides weaker constraints for the underlying gauge structure.

PACS number(s): 14.70.Pw, 12.60.Cn, 13.10.+q, 13.85.Qk

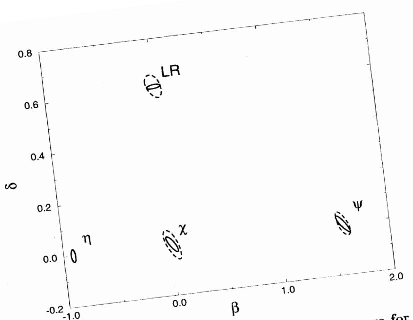
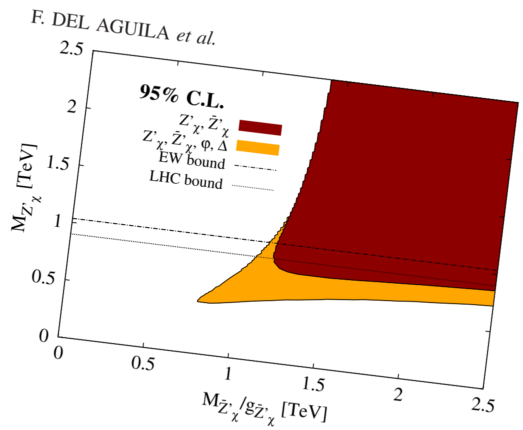


FIG. 3. 90% confidence level ($\Delta\chi^2 = 4.6$) contours for β vs δ for the typical models at the LHC. $M_{Z'} = 1$ TeV. Only statistical error bars for the probes are used. Dashed lines are determined by fixing $S_1 = 0$, while the solid ones correspond to setting $S_2 = 0$ as well.



PHYSICAL REVIEW D **84,** 015015 (2011)

Impact of extra particles on indirect Z' limits

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We study the possibility of relaxing the indirect limits on extra neutral vector bosons by their interplay with additional new particles. They can be systematically weakened, even below present direct bounds at colliders, by the addition of more vector bosons and/or scalars designed for this purpose. Otherwise, they appear to be robust.

PACS numbers: 12.60.Cn, 12.10.Dm

DOI: 10.1103/PhysRevD.84.015015

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The Standard Paradigm

- **MSSM at TeV scale** (no LHC signal)
- **LSP WIMPs** (no unambiguous signal)
- (Possibly) **GUT at unification scale** (gauge unification)
- **Seesaw model for m_ν**
  - **Leptogenesis**
  - (Possibly) **GUT relations for couplings** (large representations?)
  - **Flavor symmetries** (discrete, global, gauge)
- **SUSY breaking in hidden sector**
- **Assumptions of naturalness, uniqueness, minimality**

Beyond the MSSM

Even if TeV-supersymmetry found, MSSM may not be the full story

Most of the problems of standard model remain, new ones introduced
(FCNC, EDM, proton decay if no R_P)

μ problem introduced: $W_\mu = \mu \hat{H}_u \cdot \hat{H}_d, \quad \mu = \mathcal{O}(\text{electroweak})$

Remnants of GUT/Planck scale physics may survive to TeV scale

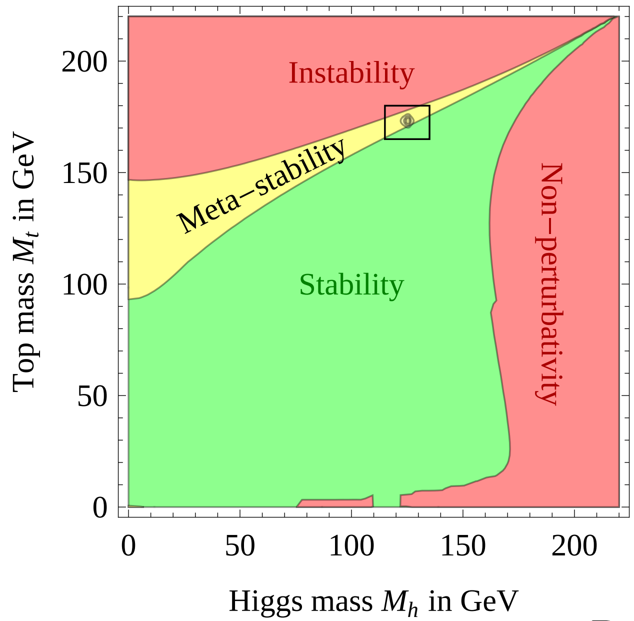
Specific string constructions often have extended gauge groups, exotics, extended Higgs/neutralino sectors (defect or hint?)

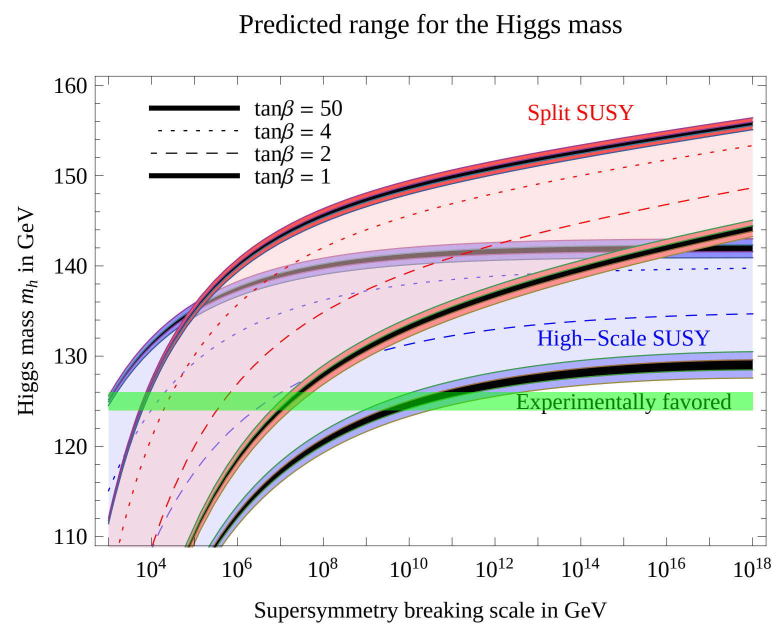
Ingredients of 4d GUTs hard to embed in string, especially large Higgs representations, Yukawa relations

Important to explore alternatives/extensions to MSSM

Naturalness or Tuning

- **ATLAS/CMS: no sign of supersymmetry or other new physics**
- **Higgs-like particle: consistent with elementary Higgs**
  - **SM: rather light** (metastable vacuum or new physics below 10^{11} GeV)
  - **MSSM: rather heavy** (need heavy stop or large mixing)





Degrassi et al, 1205.6497

- **Higgs mass^2 very unnatural (tuning by 10^{34}) unless TeV physics**
  (supersymmetry, alternative EWSB, large dimensions)

- **Is naturalness a good guide? cf dark energy (tuning by 10^{120})**
  (environmental solution?)

- **Even for higher-scale new physics: little (baby) hierarchy problem**
  (but reduces FCNC, EDM constraints)

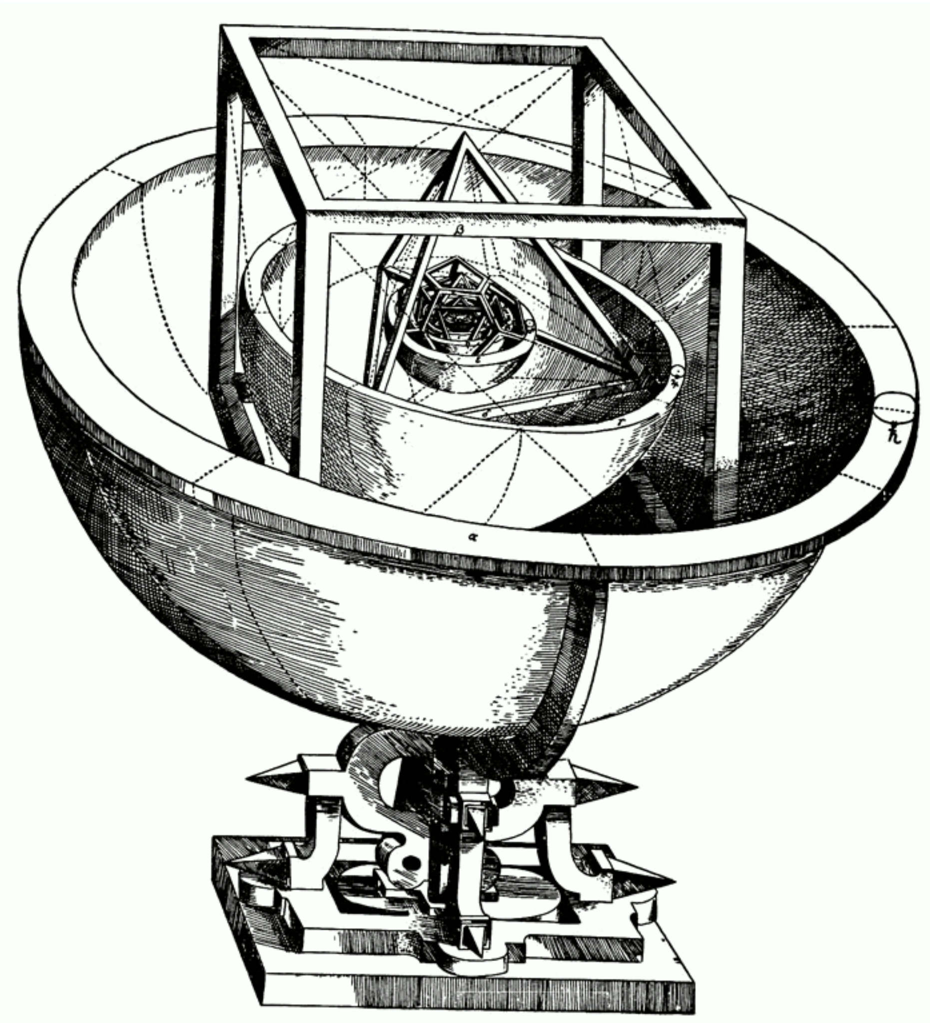
Uniqueness or Environment

- **Gauge interactions: determined by symmetry**
  (but groups, representations, SSB)

- **Yukawa interactions (flavor physics): apparently unconstrained, unless new symmetries/principles (local, global, discrete, stringy)**

- **The uniqueness paradigm (cf., Kepler's Mysterium Cosmographicum)**
  - **Enormous effort (especially ν) to understand spectrum/mixings by flavor symmetries/textures, usually in seesaw context**
    (tri-bimaximal, bimaximal, complementarity, GUT + flavor, lopsided, Froggatt-Nielsen, haze, loops, $\not{R}_p$)
  - **$\theta_{13} \neq 0, \theta_{23} \neq 45^\circ$ excludes many models or requires perturbations**

Kepler's Mysterium Cosmographicum



- **The environmental paradigm** (cf., planetary orbits)
  - No simple explanation of parameters
    (but scales/hierarchies by FN-like powers or exponentials?)
  - String landscape: may be $\gtrsim 10^{600}$ vacua with no known selection principle
  - Subset habitable, with different groups, remnants, hierarchy mechanisms, parameters
  - Multiverse sampled by eternal inflation?
  - Environmental selection? (A word?)

Early Speculations

Horatio:
O day and night, but this is wondrous strange!

Hamlet:
And therefore as a stranger give it welcome.
There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.

(William Shakespeare: Hamlet, 1603)

- **The environmental paradigm** (contd.)
  - Underlying constraints often too complicated to unravel
  - Version of anarchy
- **Distinction of paradigms critical**

The String Landscape

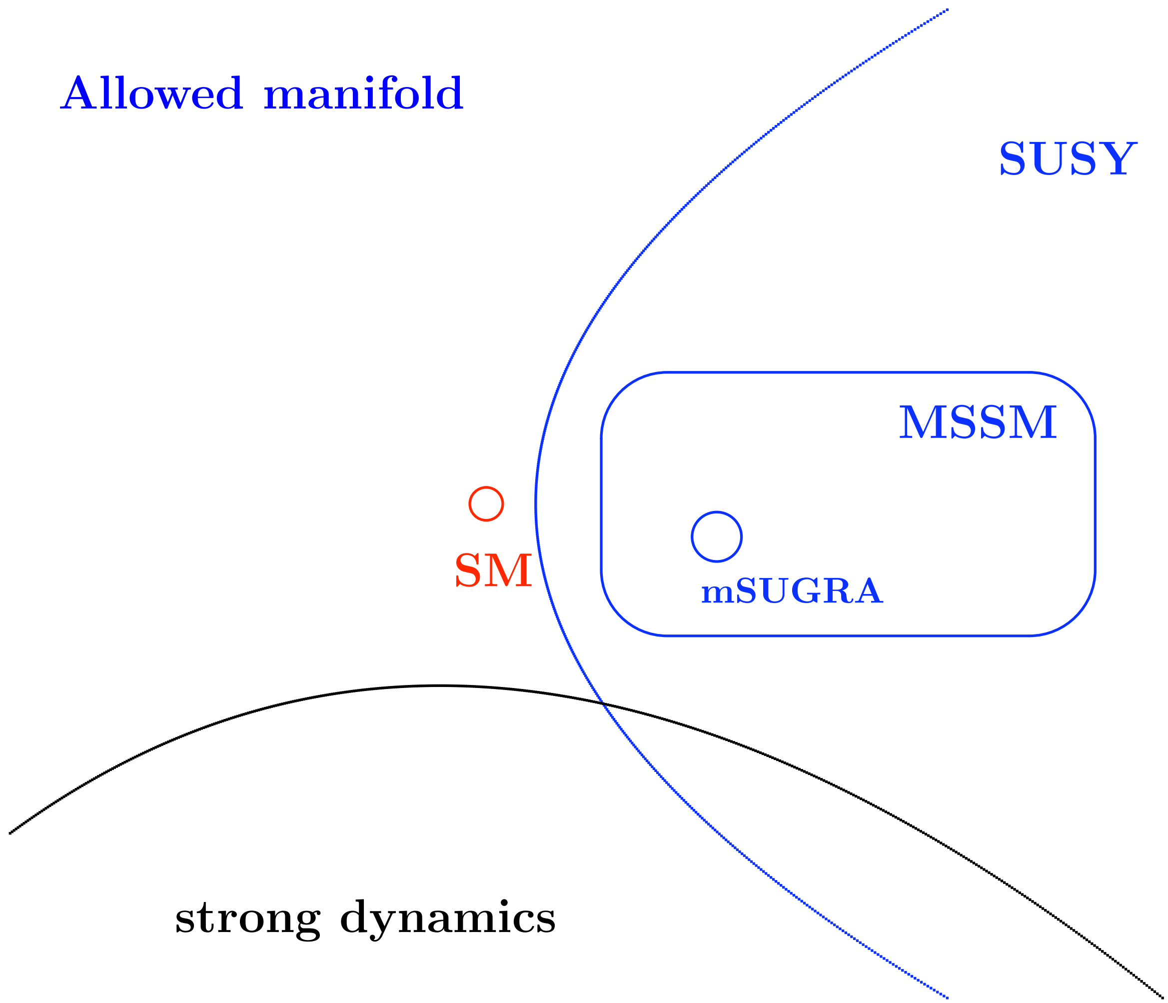
- String theory very promising (finite quantum gravity & other interactions)
- However, may be enormous *landscape* of vacua ($> 10^{600}$)
- Many contain SM or MSSM
- Many involve TeV-scale *remnants* (e.g., Z', exotics, extended Higgs, quasi-hidden sectors) beyond the MSSM (hint?)
- Top-down remnants may not be minimal or motivated by SM problems

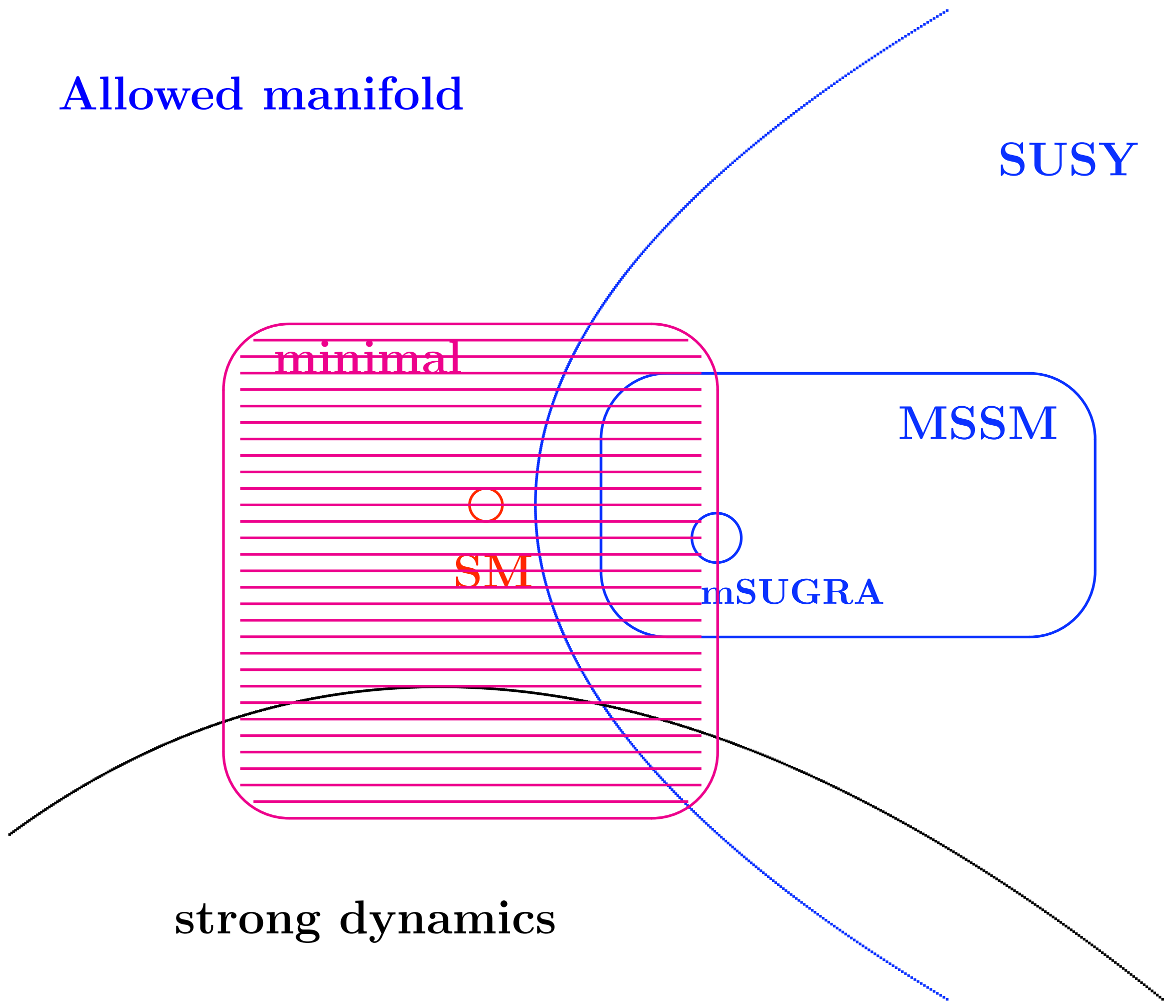
Minimality or Remnants

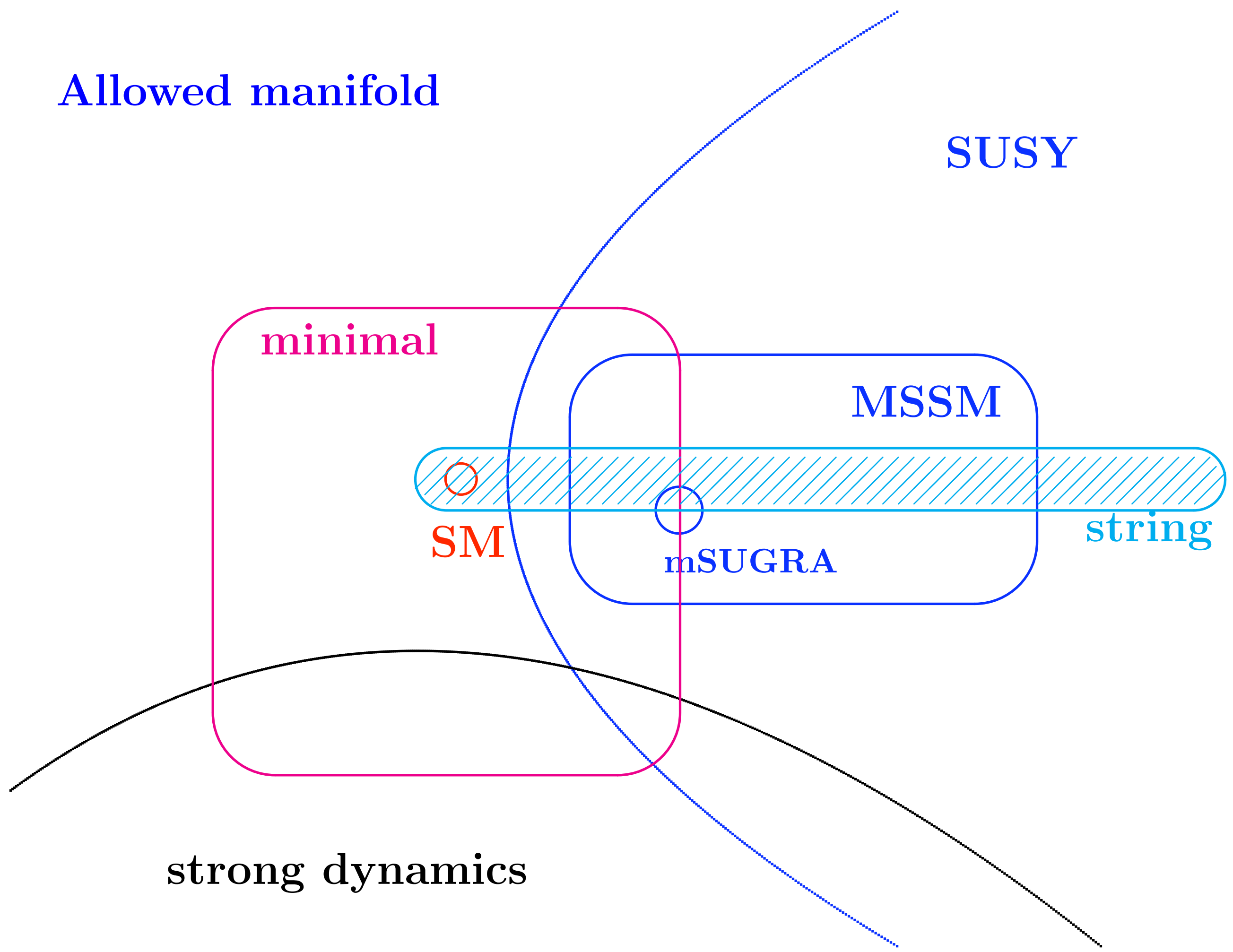
- **Some bottom-up ideas unlikely to emerge from simple/perturbative string constructions**
  (e.g., high-dimensional representations)

- **Top-down may suggest new physical mechanisms** (e.g., string instantons: exponentially suppressed μ, Majorana or Dirac m_ν, etc)

- **Important to map string-likely or unlikely classes of new physics and mechanisms** (and contrast with field theory)


Allowed manifold
SUSY
MSSM
SM
mSUGRA
strong dynamics


Allowed manifold
SUSY
minimal
MSSM
SM
mSUGRA
strong dynamics


Allowed manifold
SUSY
minimal
MSSM
SM
mSUGRA
string
strong dynamics

Typical Stringy Effects

- Z' (or other gauge)
- **Extended Higgs/neutralino** (doublet, singlet)
- **Quasi-chiral Exotics**
- **Leptoquark, diquark, $\not{R}_P$ couplings**
- **Family non-universality** (from different origins) (Yukawas, $U(1)'$)
- **Various ν mass mechanisms** (HDO, string instantons: non-minimal seesaw, Weinberg op, Dirac, sterile)
- **(Quasi-)hidden sectors** (strong coupling? SUSY breaking? dark matter? random?); **may be portals** (exotics, Z', Higgs)

- *Perturbative* **global symmetries from anomalous $U(1)'$**
  (exponentially-suppressed breaking)

- **Nonstandard hypercharge embeddings/normalizations**

- **Fractionally charged color singlets** (e.g., $\frac{1}{2}$)
  (confined?, stable relic? millicharged?)

- **Large/warped dimensions, low string scale**
  (TeV black holes, stringy resonances)

- **Time/space/environment-varying couplings**

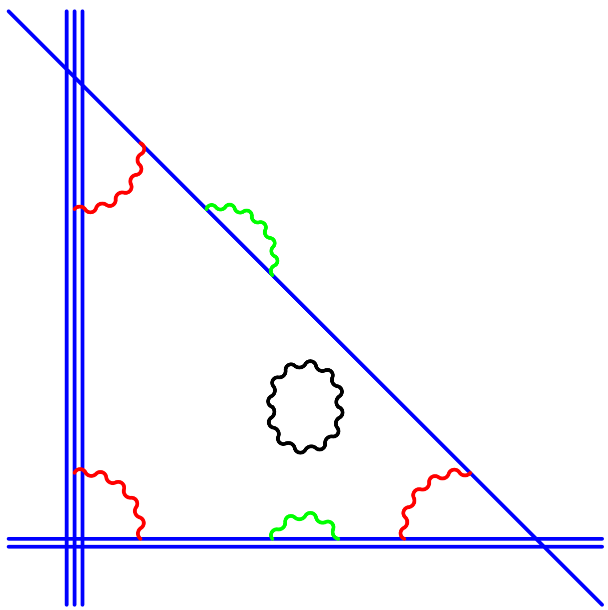
- **LIV, VEP** (speeds, decays, [oscillations] of HE γ, e, gravity waves, [ν's])

Surveying the Landscape

- **Counting of group factors, families, etc; MSSM and beyond**
  - Denef, Douglas [0404116, 0411183]
  - Kumar, Wells [0409218]
  - DeWolfe, Giryavets, Kachru, Taylor [0411061]
  - Blumenhagen, Gmeiner, Honecker, Lust, Weigand [0411173, 0510170]
  - Dienes, Dudas, Gherghetta [0412185]
  - Arkani-Hamed, Dimopoulos, Kachru [0501082]
  - Kumar [0601053]
  - Dienes [0602286]; Dienes, Lennek, Senechal, Wasnik [0704.1320]
  - Anastasopoulos, Dijkstra, Kiritsis, Schellekens [0605226]
  - Shelton, Taylor, Wecht [0607015]
  - Gmeiner [0608227]; Gmeiner, Honecker [0708.2285]
  - Douglas, Kachru [0610102]
  - Blumenhagen, Kors, Lust, Stieberger [0610327]
  - Denef, Douglas, Kachru [0701050]
  - AbdusSalam, Conlon, Quevedo, Suruliz [0709.0221]
  - Balasubramanian, de Boer, Naqvi [0805.4196]
  - Gabella, He, Lukas [0808.2142]
  - Anderson, Gray, Lukas, Palti [1106.4804]
  - Schellekens [1306.5083]
  - Nibbelink, Loukas [1308.5145]

- **MSSM-like**
  - **Remnants common (but often explicity excluded)**
  - **Extensions of MSSM quivers needed by stringy constraints**

Intersecting Brane (Type IIA) Constructions



- $U(N)$ from N D6 branes
  (fill 3 of the 6 extra dimensions)

- Adjoints, bifundamentals (open); gravitons (closed)

- Also, symmetric, antisymmetric; $SO(2N), Sp(2N)$

- Families from multiple intersections
  (3-cycles wrapping 6d)

- Yukawa interactions $\sim \exp(-A_{ijk}) \rightarrow$ hierarchies

- Existing models: additional gauge factors, Higgs, chiral matter

- Global $U(1)$' s (may be broken by nonperturbative string instantons)

Tadpoles and Extended MSSM Quivers

Implications of String Constraints for Exotic Matter and Z's Beyond the Standard Model, M. Cvetič, J. Halverson, PL, JHEP 1111,058 (1108.5187);
Anomaly Nucleation Constrains $SU(2)$ Gauge Theories, J. Halverson (1310.1091)

- **Intersecting brane type IIA constructions (and others): tadpole cancellation conditions stronger than anomaly cancellation in augmented field theory (for $N_a = 1, 2$)**
  (FT with anomalous $U(1)$'s and Chern-Simons terms)
  - **$U(N_a)$ from stack of N_a D6 branes:**

$$N_a \geq 2: \qquad \#a - \#\overline{a} + (N_a + 4)\ (\#\square\!\square_a - \#\overline{\square\!\square}_a) + (N_a - 4)\ (\#\genfrac{}{}{0pt}{}{\square}{\square}_a - \#\overline{\genfrac{}{}{0pt}{}{\square}{\square}}_a) = 0$$

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

  - **$SU(N_a)^3$ triangle anomaly condition for $N_a \geq 3$**
  - **Landscape view: all vacua must be consistent**

- "Anomalous" $U(1)$ from trace generator of $U(N)$ usually acquires Stuckelberg mass near string scale M_s
  - Anomalies cancelled by Chern-Simons
  - $U(1) \Rightarrow$ global symmetry on (perturbative) superpotential
  - May be broken by non-perturbative D-instantons (exponentially suppressed)

- Linear combination $\sum q_x U(1)_x$ may be massless, non-anomalous if

$$-q_a N_a\ (\#\Box\Box_a - \#\overline{\Box\Box}_a + \#\begin{smallmatrix}\Box\\\Box\end{smallmatrix}_a - \#\overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}_a) + \sum_{x\neq a} q_x N_x\ (\#(a,\overline{x}) - \#(a,x)) = 0, \qquad N_a \geq 2$$

$$q_a\ \frac{\#(a) - \#(\overline{a}) + 8(\#\Box\Box_a) - \#\overline{\Box\Box}_a)}{3} + \sum_{x\neq a} q_x N_x\ (\#(a,\overline{x}) - \#(a,x)) = 0, \qquad N_a = 1$$

  - Require one linear combination $\Rightarrow$ weak hypercharge, Y
  - May be additional massless combinations, broken by Higgs singlet VEVs $\Rightarrow$TeV-scale Z' (even for $M_s = \mathcal{O}(M_{pl})$)

New Matter and Z's

- **Most quivers with just MSSM chiral matter don't satisfy tadpole constraints** (none for 3 nodes with no vector pairs)

- **Systematically add matter to MSSM quivers to satisfy tadpole and hypercharge conditions** (eight 3 and 4-node hypercharge embeddings)
  - **Up to 5 additional fields**
  - **Don't allow purely vector pairs** (typically acquire M_s-scale masses)
  - **Allow quasi-chiral pairs** (vector under MSSM; chiral under "anomalous" or additional non-anomalous $U(1)$'s)
  - **May also exclude fractional charge, heavy chiral states, no $H_d - L$ distinction**

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

- **MSSM singlets with anomalous $U(1)$ charge**
  - **Perturbative NMSSM-like singlet** $(S_\mu H_u H_d)$
    (alternative: D-instanton)
  - **Perturbative ν_L^c-like singlet** $(\nu_L^c H_u L)$
    (alternative: Dirac or Weinberg op by D-instanton)
  - **Random**

- **Isotriplets** $(Y = 0)$

- **Quasi-chiral pairs: lepton/Higgs doublets; down-type quark isosinglets; nonabelian singlets** ($Y = Q = \pm 1$)
  (+ some up-type quark isosinglets, quark isodoublets,
  shifted lepton/Higgs doublets ($Q = (\pm 1, \pm 2)$))
  - Mass by $SX\bar{X}$ (S =MSSM singlet) or $X\bar{X}$ (D-instantons)
  - Produce quarks/scalar partners by QCD
  - Cascade decays to lightest
  - Decay: mixing, lepto/di-quark, HDO (rapid, delayed, quasi-stable)
  - Many have $H_d - L$ distinction (necessary for L and R-parity conservation)

- **Small number fractional charges, chiral fourth family** (Landau poles), **shifted fourth families:**
  $(3, 2)_{-\frac{5}{6}}, (\bar{3}, 1)_{\frac{1}{3}}, (\bar{3}, 1)_{\frac{4}{3}}, (1, 2)_{-\frac{3}{2}}, (1, 3)_1$

- **Quivers with additional $U(1)'$ gauge symmetry**
  - $\lesssim$ 50% are family universal for q_L, L, u_L^c, d_L^c, and e_L^c
  - Family non-universal (quiver distinct): GIM violation, FCNC (B_s anomalies?)

	Multiplicity of Quivers				
Hypercharge	$U(1)'$	H_d Candidate	Fam. Univ	$S_\mu H_u H_d$	$L H_u \nu_L^c$
$(-\frac{1}{3}, -\frac{1}{2}, 0)$	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

Conclusions

- **String landscape/eternal inflation: physics may be (partially) environmental**

- **From bottom up: there may be more at TeV scale than MSSM**

- **From top down: there may be more at TeV scale than MSSM**
  (e.g., Z', extended Higgs/neutralino, quasi-chiral exotics, nonstandard ν)

- **Important to delineate difference between string possibilities and field theory possibilities**

A TeV-Scale Z'

Review: Rev.Mod.Phys.81,1199 (arXiv:0801.1345)

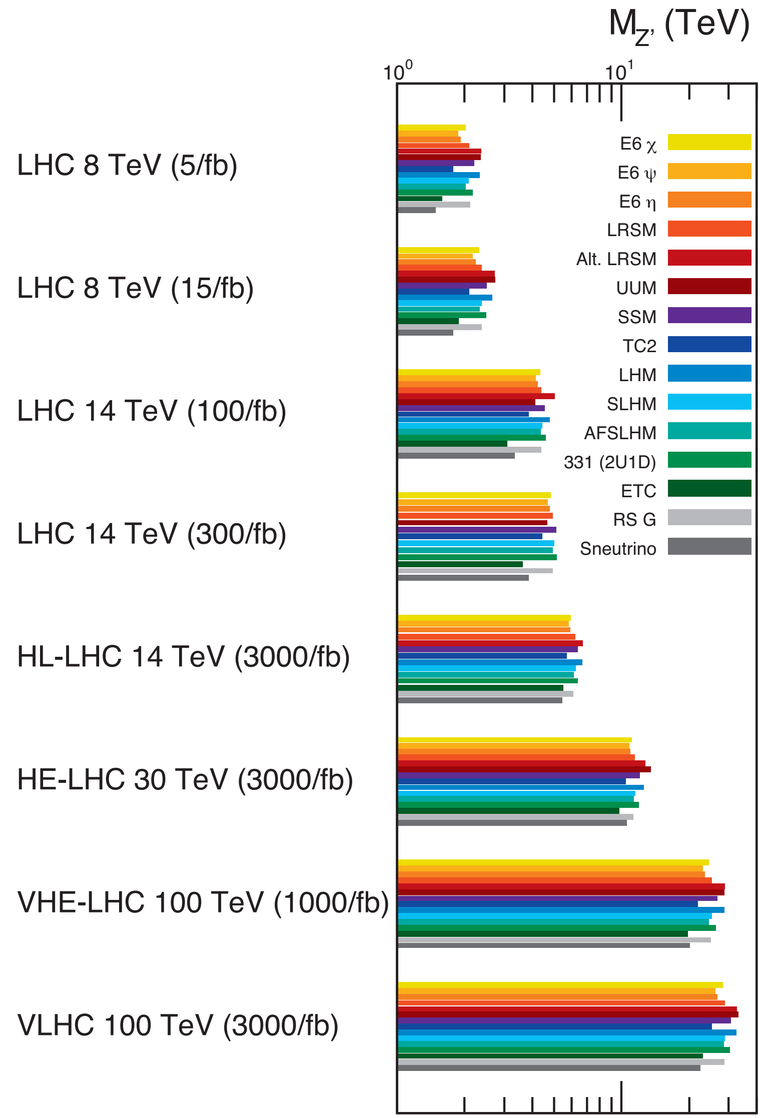
- **Strings, GUTs, DSB, little Higgs, LED often involve extra Z'**
  (harder to break $U(1)'$ factors than non-abelian: remnants)

- **Typically $M_{Z'} \gtrsim 2 - 3$ TeV for electroweak coupling**
  (LHC, Tevatron, LEP 2, WNC); $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)

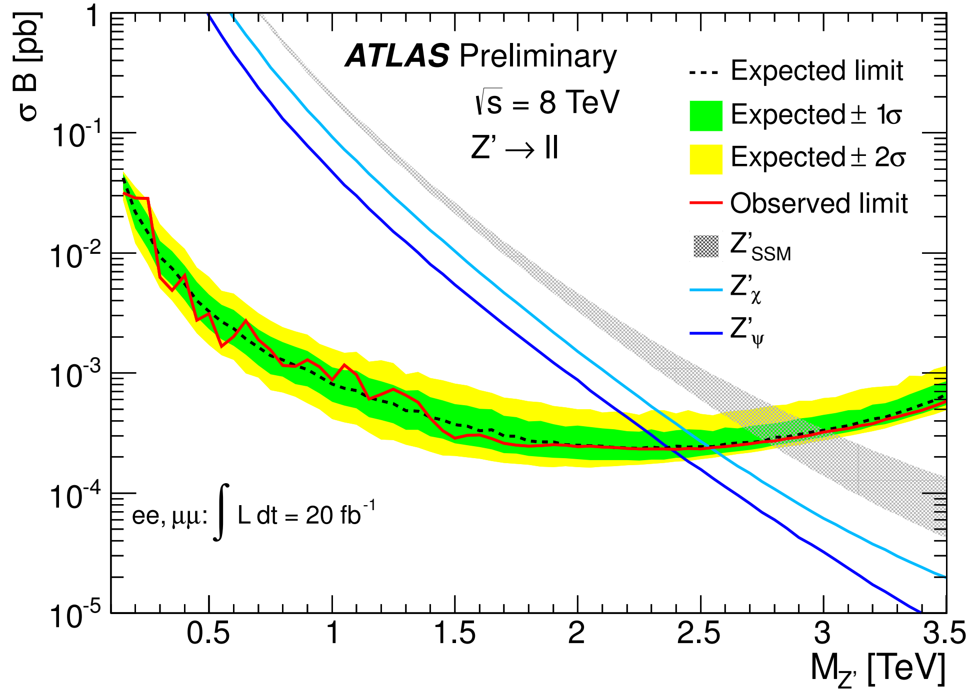
- **Discovery to $M_{Z'} \sim 5 - 6$ TeV at LHC-14, higher in e^-e^+**
  $(pp \to \mu^+\mu^-, e^+e^-, q\bar{q})$ (depends on couplings, exotics, sparticles)

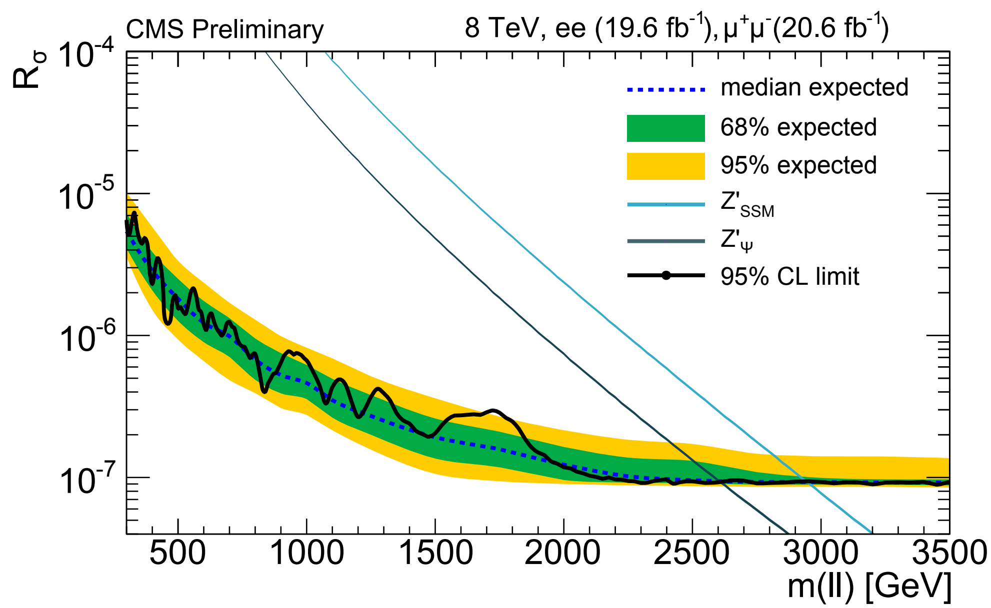
- **LHC diagnostics to 1-3 TeV** (BR's, asymmetries, polarizations,
  y distributions, associated production, rare decays);
  higher for ILC/CLIC/TLEP

- **Light** (150-300 GeV) **leptophobic, TeV-scale** (FCNC), **or very light**
  ($\lesssim$ 10 GeV) **Z' portal suggested by recent anomalies/DM**



Godfrey, Martin, 1309.1688





String Z'

- Non-anomalous, descending through non-abelian group ($E_6, SO(10)$, Pati-Salam (may be T_{3R}, T_{BL}, E_6 or “random”))

- Anomalous $U(1)'$, e.g., from $U(n)$ or $U(1)$ branes
  - Stückelberg masses $\sim M_{str}$
  - Z' and Chern-Simons term may be observable for $M_{str} \sim$ TeV
  - Large M_{str}: may be anomaly-free combinations (in addition to Y); often family non-universal

Implications of a TeV-scale $U(1)'$

- Couplings $\rightarrow$ clues about embedding into underlying theory
- Natural solution to μ problem: $W \sim h_s S H_u H_d \rightarrow \ \mu_{eff} = h_s \langle S \rangle$
  ("stringy version" of NMSSM)
- Supersymmetry: $SU(2) \times U(1)$ and $U(1)'$ breaking scales *both* set by SUSY breaking scale (unless flat direction)
- Extended Higgs sector
  - Relaxed mass limits, couplings, parameters (e.g., $\tan \beta \sim 1$)
  - Higgs singlets needed to break $U(1)'$
  - Doublet-singlet mixing, extended neutralino sector
    ($\rightarrow$ non-standard collider signatures)

- Extended neutralino sector
  - Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  - Additional cold dark matter, $g_\mu - 2$ possibilities
- Exotics (anomaly-cancellation)
  - Non-chiral wrt SM but chiral wrt $U(1)'$
  - May decay by mixing; by diquark or leptoquark coupling; or be quasi-stable
- Z' decays into sparticles/exotics (SUSY factory)
- Flavor changing neutral currents (for non-universal $U(1)'$ charges)
  - Tree-level effects in B decay competing with SM loops (or with enhanced loops in MSSM with large $\tan\beta$)
  - $B_s - \bar{B}_s$ mixing, B_d penguins
  - $t\bar{t}$ forward-backward asymmetry (probably excluded)

- **Non-universal charges: MSW-type effects** (apparent CPT violation)
- $Z' - \tilde{Z}'$ **mediation of SUSY breaking**
- **Constraints on neutrino mass generation**
  - Various versions allow or exclude Type I or II seesaws, extended seesaw, small Dirac by HDO or non-holomorphic soft; stringy Weinberg operator, Majorana seesaw, small Dirac by string instantons; sterile mixing
    (e.g., Kang, PL, Li; Phys. Rev. D 71, 015012 (2005) [hep-ph/0411404])
- **Large A term and possible tree-level CP violation**
  (no new EDM constraints) $\rightarrow$ **electroweak baryogenesis**

Extended Higgs Sector

- Standard model singlets S_i and additional doublet pairs $H_{u,d}$ very common
- Additional doublet pairs
  - Richer spectrum, decay possibilities (anomalies?)
  - May be needed (or expand possibilities for) quark/lepton masses/mixings (e.g., stringy symmetries may restrict single Higgs couplings to one or two families)
  - Extra neutral Higgs $\rightarrow$ FCNC (suppressed by Yukawas)
  - Significantly modify gauge unification (unless compensated)

Higgs singlets S_i

- Standard model singlets common in string constructions
- Needed to break extra $U(1)'$ gauge symmetries
- Solution to μ problem ($U(1)'$, NMSSM, nMSSM, sMSSM)

$$W \sim h_s S H_u H_d \rightarrow \ \mu_{eff} = h_s \langle S \rangle$$

- $F(D)$ terms allow larger MSSM-like Higgs mass
- Modified couplings, parameter ranges, branching ratios
- Singlet-doublet mixing
- Large A term and possible tree-level CP violation $\rightarrow$ electroweak baryogenesis

Quasi-Chiral Exotics

- Often find exotic (wrt $SU(2) \times U(1)$) quarks/leptons at TeV scale
  - Assume non-chiral wrt SM gauge group (strong constraints on SM chiral from large Yukawas ($\Rightarrow$ Landau poles), precision EW)
  - Can be chiral wrt extra $U(1)'$s or other extended gauge
  - Usually needed for $U(1)'$ anomaly cancellation
  - Modify gauge unification unless in complete GUT multiplets
  - Strings typically yield (anti-) (bi-) fundamentals, adjoints, (anti-) symmetrics
  - May also be quasi-hidden, shifted charges, or fractional charges

- Examples in 27-plet of E_6
  - $D_L + D_R$ ($SU(2)$ singlets, chiral wrt $U(1)'$)
  - $\begin{pmatrix} E^0 \\ E^- \end{pmatrix}_L + \begin{pmatrix} E^0 \\ E^- \end{pmatrix}_R$ ($SU(2)$ doublets, chiral wrt $U(1)'$)

- Pair produce $D + \bar{D}$ by QCD processes (smaller rate for exotic leptons)

- D or $\tilde{D}$ decay by
  - $D \to u_i W^-,\ D \to d_i Z,\ D \to d_i H^0$ if driven by $D - d$ mixing (not in minimal E_6; FCNC)
  - $\tilde{D} \to$ quark jets if driven by diquark operator $\bar{u}\bar{u}\bar{D}$, or quark jet $+$ lepton for leptoquark operator $lq\bar{D}$ (still have stable LSP)
  - May be stable at renormalizable level due to accidental symmetry (e.g., extended gauge group) $\to$ hadronizes and escapes or stops in detector (quasi-stable from HDO $\to \tau < 1/10$ yr) (Kang, PL, Nelson, Phys.Rev. D77, 035003 (arXiv:0708.2701))

- **Applications: $H \to \gamma\gamma$, dark matter, baryogenesis, B-mixing/decays, FCNC, flavor structure, A^b_{FB}, gauge mediation**
  - PL, London [PR D38,886]
  - Choudhury, Tait, Wagner [0109097]
  - del Aguila, de Blas, Perez-Victoria [0803.4008]
  - Endo, Hamaguchi, Ishikawa, Iwamoto, Yokozaki [1108.3071,1112.5653,1212.3935]
  - Martin, James D. Wells [1206.2956]
  - Bonne, Moreau [1206.3360]
  - Joglekar, Schwaller, Wagner [1207.4235,1303.2969]
  - Botella, Branco, Nebot [1207.4440]
  - Arkani-Hamed, Blum, D'Agnolo, Fan [1207.4482]
  - Kearney, Pierce, Weiner [1207.7062]
  - Batell, Gori, Wang [1209.6382]
  - Cacciapaglia, Deandrea, Perries, Sordini, Panizzi [1211.4034]
  - Garberson, T. Golling [1301.4454]
  - Buras, Girrbach, Ziegler [1301.5498]
  - Aguilar-Saavedra, Benbrik, Heinemeyer, Perez-Victoria [1306.0572]
  - Alves, Barreto, Camargo, Dias [1306.1275]
  - Aguilar-Saavedra [1306.4432]
  - Ishiwata, Wise [1307.1112]
  - Alloul, Frank, Fuks, de Traubenberg [1307.1711]
  - Fairbairn, Philipp Grothaus [1307.8011]
  - Altmannshofer, Bauer, Carena [1308.1987]
  - Halverson [tbp]

Small neutrino masses

- Many mechanisms for small m_ν, both Majorana and Dirac
- Minimal Type I seesaw
  - Bottom-up motivation: no gauge symmetries prevent large Majorana mass for ν_R
  - Connection with leptogenesis
  - Argument that L *must be violated* is misleading
    [non-gravity: large 126 of $SO(10)$ or HDO added by hand]
    [gravity: $m_\nu \lesssim \nu_{EW}^2/\overline{M}_P \sim 10^{-5}$ eV (unless LED); often much smaller]
  - New TeV or string scale physics/symmetries/constraints may invalidate assumptions
    [No 126 in string-derived $SO(10)$]
- Bottom-up alternatives: Higgs (or fermion) triplets, extended (TeV) seesaws, loops, R_p violation

- **String-motivated alternatives**
  (review: ARNPS, 62, 215; arXiv:1112.5992)
  - **Higher-dimensional operators (HDO)**
    [non-minimal seesaw (not GUT-like), direct Majorana (Weinberg op), small Dirac, mixed (LSND, MiniBooNE)]
  - **String instantons (exponential suppressions)**
    [non-minimal seesaw, direct Majorana, small Dirac]
  - **Geometric suppressions (large dimensions)** [small Dirac]
- **Alternatives often associated with new TeV physics, electroweak baryogenesis, etc.**

MSSM hypercharge embeddings

(Ibanez, Marchesano, Rabadan; Anastasopoulos, Dijkstra, Kiritsis, Schellekens)

- **Three-node embeddings** $(U(3)_a \times U(2)_b \times U(1)_c)$

$$\text{Madrid:} \qquad U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c$$

$$\text{non-Madrid:} \qquad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b$$

- **Four-node embeddings** $(U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d)$

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c + \frac{1}{2}U(1)_d \qquad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b + \frac{1}{2}U(1)_d$$

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c + \frac{3}{2}U(1)_d \qquad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b$$

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c \qquad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b + U(1)_d,$$

• 105 Madrid 3-node quivers (≤ 5 additions)

Multiplicity	Matter Additions				
4	$\square\!\square_b,\ (1,3)_0$	$\square\!\square_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(\overline{a},\overline{b}),\ (\overline{3},2)_{-\frac{1}{6}}$
4	$\square\!\square_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$			
4	$\overline{\square\!\square}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$			
4	$\square\!\square_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\overline{\square\!\square}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\square\!\square_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(\overline{a},\overline{b}),\ (\overline{3},2)_{-\frac{1}{6}}$
4	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$			
4	$\overline{\boxminus}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$		
4	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(\overline{a},\overline{c}),\ (\overline{3},1)_{-\frac{2}{3}}$	$\square\!\square_c,\ (1,1)_1$
4	$\square\!\square_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$
4	$\overline{\square\!\square}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$
4	$\overline{\square\!\square}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$		
4	$\overline{\square\!\square}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$\overline{\square\!\square}_b,\ (1,3)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\boxminus_b,\ (1,1)_0$				
4	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$\overline{\square\!\square}_b,\ (1,3)_0$	$\overline{\square\!\square}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	
4	$\overline{\square\!\square}_b,\ (1,3)_0$	$\overline{\square\!\square}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	

Multiplicity	Matter Additions				
4	$\overline{\square\square}_b$, $(1,3)_0$	$\overline{\square\square}_b$, $(1,3)_0$	$\overline{\square\square}_b$, $(1,3)_0$	$\overline{\boxminus}_b$, $(1,1)_0$	$\overline{\boxminus}_b$, $(1,1)_0$
4	$\overline{\square\square}_b$, $(1,3)_0$	$\overline{\square\square}_b$, $(1,3)_0$	$\boxminus_b$, $(1,1)_0$		
1	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\square\square_b$, $(1,3)_0$	$\boxminus_b$, $(1,1)_0$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$	
1	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\square\square_b$, $(1,3)_0$	$\boxminus_b$, $(1,1)_0$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$	
1	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\overline{\square\square}_b$, $(1,3)_0$	$\boxminus_b$, $(1,1)_0$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$	
1	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\overline{\square\square}_b$, $(1,3)_0$	$\boxminus_b$, $(1,1)_0$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$	
1	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\overline{\boxminus}_b$, $(1,1)_0$	$\overline{\boxminus}_b$, $(1,1)_0$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$	
1	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\overline{\boxminus}_b$, $(1,1)_0$	$\overline{\boxminus}_b$, $(1,1)_0$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$	
1	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\overline{\boxminus}_b$, $(1,1)_0$	$(b,\overline{c})$, $(1,2)_{-\frac{1}{2}}$	(b,c), $(1,2)_{\frac{1}{2}}$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\overline{\boxminus}_b$, $(1,1)_0$	$(b,\overline{c})$, $(1,2)_{-\frac{1}{2}}$	(b,c), $(1,2)_{\frac{1}{2}}$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$
1	$(a,\overline{b})$, $(3,2)_{\frac{1}{6}}$	$(b,\overline{c})$, $(1,2)_{-\frac{1}{2}}$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$	$(\overline{a},\overline{c})$, $(\overline{3},1)_{-\frac{2}{3}}$	$\square\square_c$, $(1,1)_1$
1	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\overline{\square\square}_b$, $(1,3)_0$	$\overline{\boxminus}_b$, $(1,1)_0$	$\overline{\boxminus}_b$, $(1,1)_0$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\overline{\square\square}_b$, $(1,3)_0$	$\overline{\boxminus}_b$, $(1,1)_0$	$\overline{\boxminus}_b$, $(1,1)_0$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$
1	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\boxminus_b$, $(1,1)_0$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\boxminus_b$, $(1,1)_0$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$
1	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\boxminus_b$, $(1,1)_0$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$		
1	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\boxminus_b$, $(1,1)_0$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$		
1	$\boxminus_a$, $(\overline{3},1)_{\frac{1}{3}}$	$\overline{\square\square}_b$, $(1,3)_0$	$\overline{\square\square}_b$, $(1,3)_0$	$\boxminus_b$, $(1,1)_0$	$(a,\overline{c})$, $(3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a$, $(3,1)_{-\frac{1}{3}}$	$\overline{\square\square}_b$, $(1,3)_0$	$\overline{\square\square}_b$, $(1,3)_0$	$\boxminus_b$, $(1,1)_0$	$(\overline{a},c)$, $(\overline{3},1)_{\frac{1}{3}}$

	Multiplicity of Quivers					
Hypercharge	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

- Remove quivers leading to fractionally charged color singlets
- Require H_d quiver-distinct from 3 L-doublets
  (necessary for L, R-parity conservation)
- Perturbative NMSSM-like singlet $(S_\mu H_u H_d)$ (alternative: D-instanton)
- Perturbative ν_L^c-like singlet $(\nu_L^c H_u L)$
  (alternative: Dirac or Weinberg op by D-instanton)

	Multiplicity of Quivers				
Hypercharge	$U(1)'$	H_d Candidate	Fam. Univ	$S_\mu H_u H_d$	$L H_u \nu^c_L$
$(-\frac{1}{3}, -\frac{1}{2}, 0)$	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

- Quivers with additional $U(1)'$ gauge symmetry
- $\lesssim$ 50% are family universal for q_L, L, u^c_L, d^c_L, and e^c_L
- Family non-universal (quiver distinct): GIM violation, FCNC (B_s anomalies?)

SM Rep	Total Multiplicity	4^{th} Gen. Removed	Shifted 4^{th} Gen. Also Removed
$(1,1)_0$	4556	4556	4556
$(1,3)_0$	1290	1290	1290
$(1,2)_{-\frac{1}{2}}$	631	619	619
$(1,2)_{\frac{1}{2}}$	619	619	619
$(\bar{3},1)_{\frac{1}{3}}$	478	466	458
$(3,1)_{-\frac{1}{3}}$	458	458	458
$(1,1)_1$	262	250	250
$(1,1)_{-1}$	250	250	250
$(1,2)_{-\frac{3}{2}}$	101	101	93
$(1,2)_{\frac{3}{2}}$	93	93	93
$(3,2)_{\frac{1}{6}}$	46	34	34
$(\bar{3},2)_{-\frac{1}{6}}$	34	34	34
$(\bar{3},1)_{-\frac{2}{3}}$	30	18	18
$(3,1)_{\frac{2}{3}}$	18	18	18
$(1,3)_1$	8	8	0
$(3,2)_{-\frac{5}{6}}$	8	8	0
$(\bar{3},1)_{\frac{4}{3}}$	8	8	0