New Physics from the String Vacuum

- The string vacuum
- Extended MSSM quivers
- String remnants
- Small neutrino masses

Quivers: Cvetič, Halverson, PL, JHEP 1111,058 (1108.5187)

Z': Rev.Mod.Phys.81,1199 (0801.1345)

String m_ν: 1112.5992

The String Vacuum

- String vacuum enormously complicated
- Many points not consistent with what we know (but multiverse?)
- Goal 1: obtaining the MSSM
  - Possibilities for SUSY breaking/mediation, $\mu, B\mu,\ \not{R}_P, \cdots$
- Goal 2: beyond (instead of) MSSM paradigm (don't prejudge TeV)
  - (just) MSSM is not required by experimental data
  - Many string constructions involve TeV-scale *remnants* or *mechanisms* beyond the MSSM (may be hint)
- Bottom-up models of new physics usually motivated by minimality and/or solving problems

Minimality

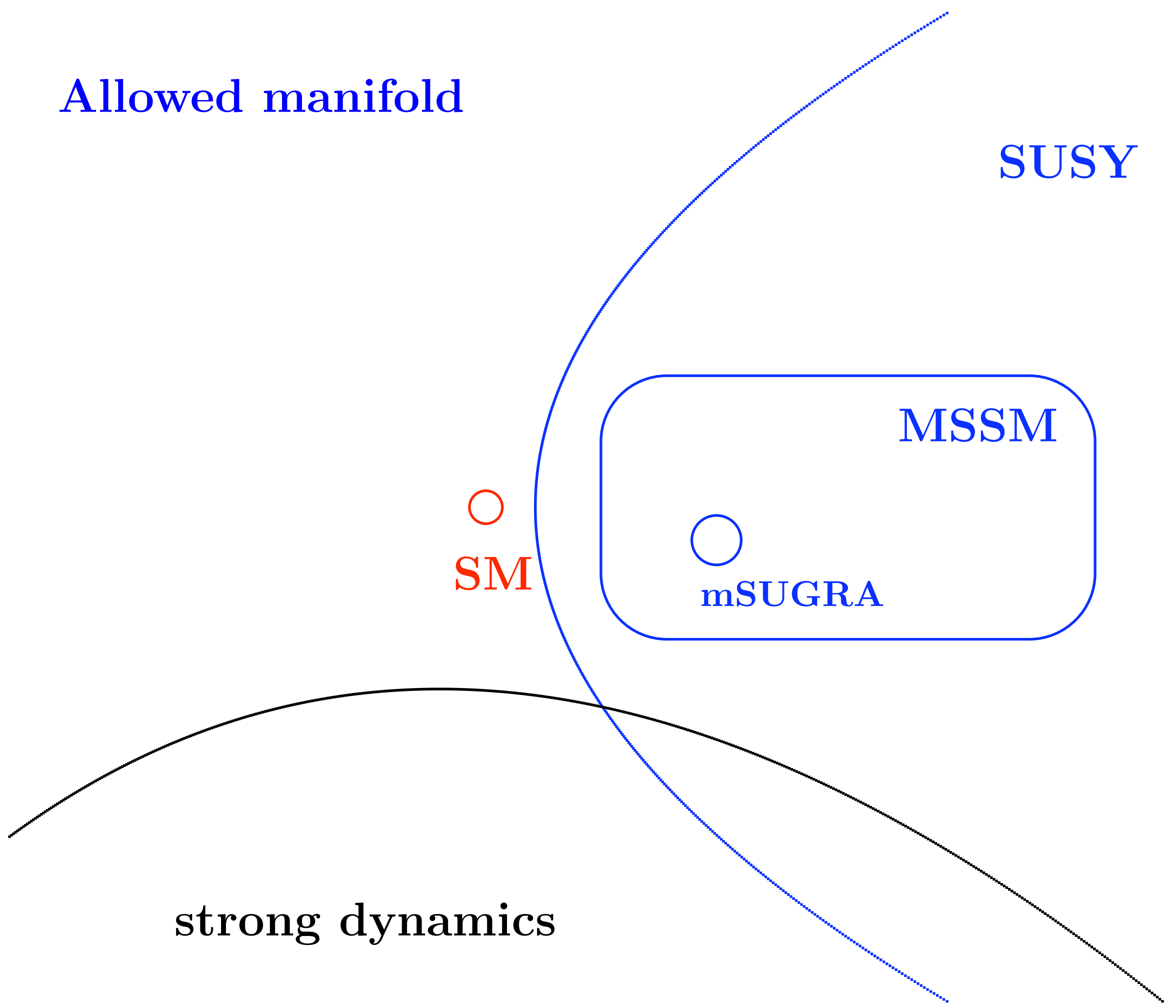

UNITED
KINGDOM
IRELAND
Dublin
Belfast
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Celtic
Sea
Irish
Sea
DENMARK
Copenhagen
Malmö
Bornholm
Kaliningrad
LITHUANIA
Vilnius
Mahilyow
Minsk
BELARUS
Hrodna
Homyel'
Gdańsk
Hamburg
Bremen
Berlin
Poznań
POLAND
Warsaw
Brest
Łódź
Wroclaw
Kiev
Rivne
UKRAINE
L'viv
Kraków
Amsterdam
Rotterdam
NETH.
Essen
Cologne
Leipzig
Brussels
Lille
BEL.
Bonn
GERMANY
Frankfurt
am Main
Prague
CZECH REPUBLIC
Brno
SLOVAKIA
Chernivtsi
Chişinau
MOLDOVA
Mykolayiv
Odesa
Iaşi
Cluj-
Napoca
Guernsey (U.K.)
Jersey (U.K.)
Paris
LUX.
Luxembourg
Stuttgart
Strasbourg
Munich
Bratislava
Vienna
AUSTRIA
Budapest
HUNGARY
ROMANIA
Bucharest
Constanta
Black
Sea
Nantes
Bay of
Biscay
FRANCE
LIECH.
Vaduz
Zürich
Bern
Geneva
SWITZ.
Lyon
Milan
Venice
Turin
Ljubljana
SLOVENIA
Zagreb
CROATIA
BOSNIA AND
HERZEGOVINA
Belgrade
Serbia
Sarajevo
Varna
BULGARIA
Sofia
Istanbul
Bordeaux
MASSIF
CENTRAL
Bilbao
Toulouse
MONACO
Genoa
SAN
MARINO
Florence
Andorra
la Vella
ANDORRA
Marseille
PYRENEES
Porto
Zaragoza
Barcelona
Corsica
ITALY
Rome
VATICAN
CITY
Adriatic
Sea
Podgorica
Montenegro
Skopje
F.Y.R.O.M.
Tirana
ALB.
Thessaloniki
Bursa
TURKEY
Izmir
PORTUGAL
Madrid
Lisbon
SPAIN
Valencia
Balearic
Sea
BALEARIC
ISLANDS
Sardinia
Naples
Tyrrhenian
Sea
Cagliari
GREECE
Athens
Aegean
Sea
Ionian
Sea
Sevilla
Gibraltar
(U.K.)
Málaga
Strait of Gibraltar
Ceuta
(SPAIN)
Alborán
Sea
Mediterranean Sea
Algiers
Palermo
Sicily
Rhodes
Crete
Melilla
(SPAIN)
Oran
Tunis
Valletta
MALTA
Scale 1: 19,500,000
Lambert Conformal Conic Projection,
standard parallels 40°N and 56°N
300 Kilometers
300 Miles
Rabat
Casablanca
MOROCCO
ALGERIA
TUNISIA

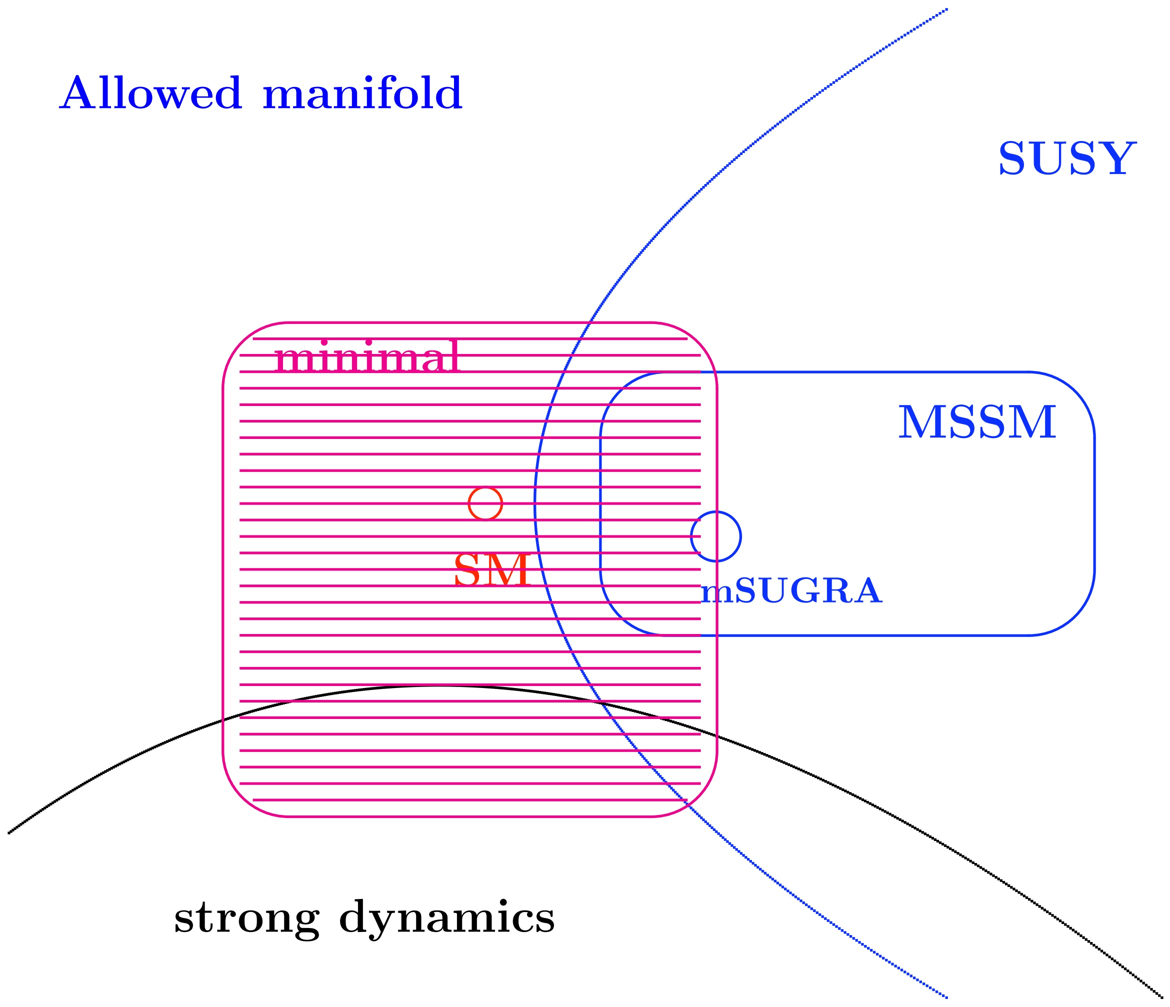
- **Top-down string remnants may not be minimal or motivated by SM problems**

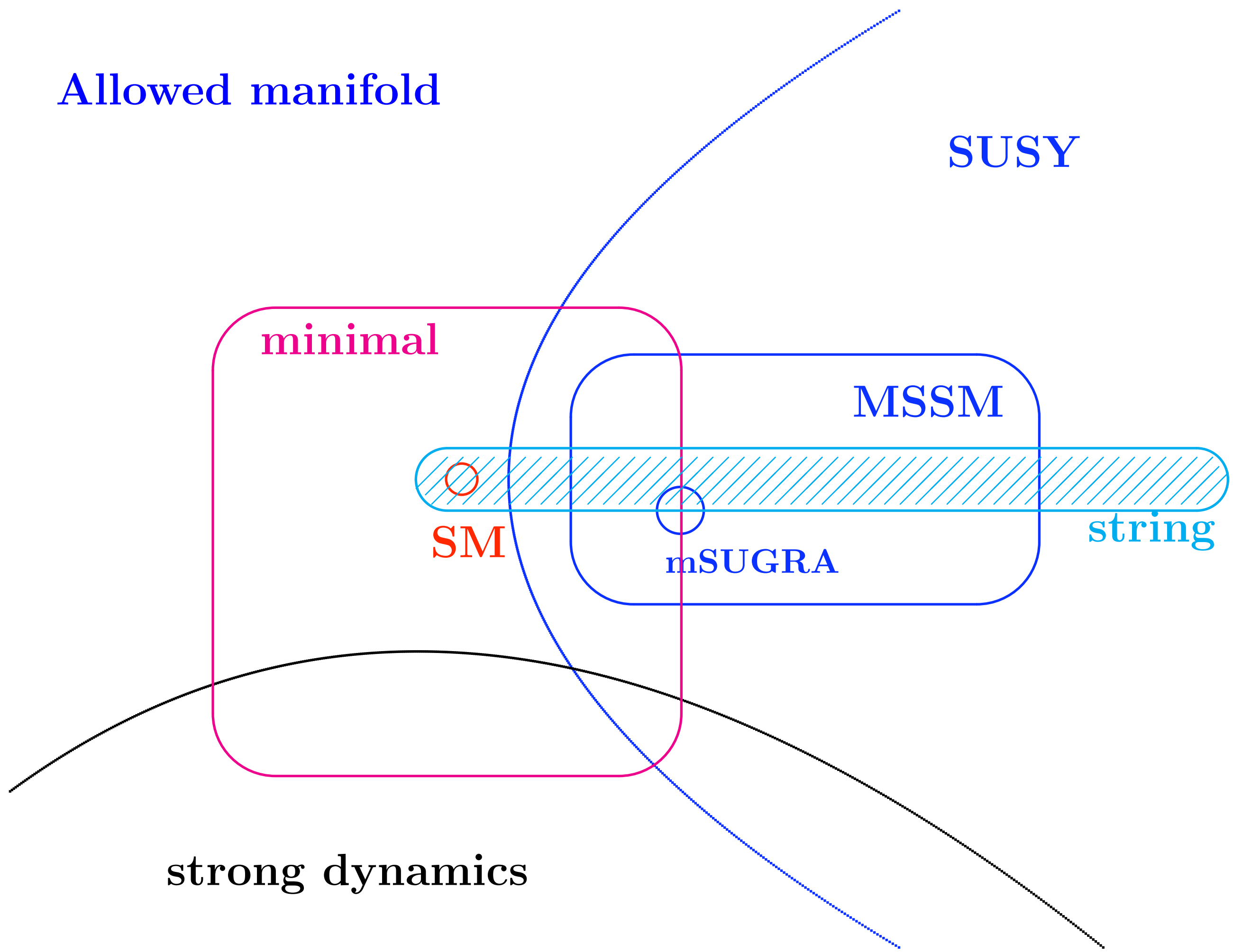
- **Top-down may suggest new physical mechanisms** (e.g., string instantons: exponentially suppressed μ, Majorana or Dirac m_ν, etc)

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

- **Goal 3: mapping of 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
string
mSUGRA
strong dynamics

- **Unlikely to find our exact vacuum**

- **Study semi-realistic/interesting vacua for suggestive features**

Typical Stringy Effects

- Z' (or other gauge)
- **Extended Higgs/neutralino** (doublet, singlet)
- **Quasi-Chiral Exotics**
- **Leptoquark, diquark, $\not{R}_P$ couplings**
- **Family non-universality** (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? portals?)

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

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

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

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

Will assume TeV scale supersymmetry

Will focus on "mild" things (not large dimensions/TeV string scale, TeV black holes, time varying couplings, multiverse, violation of the equivalence principle, Lorentz invariance violation)

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 (arXiv:1108.5187)

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

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

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

  - $SU(N_a)^3$ **triangle anomaly condition for** $N_a \geq 3$
  - **Stronger condition than augmented FT for** $N_a = 1, 2$

- “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

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

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

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

- **Hypercharge embeddings for 3-node $(U(3) \times U(2) \times U(1))$ and 4-node $(U(3) \times U(2) \times U(1) \times U(1))$ quivers containing MSSM classified**

- **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**
  - **Up to 5 additional fields**
  - **Don't allow purely vector pairs** (typically acquire M_s-scale masses)
  - **Allow quasichiral pairs** (vector under MSSM; chiral under "anomalous" or additional non-anomalous $U(1)$'s)
  - **Suggestive of quasichiral types, $U(1)'$s**
    (often family non-universal $\Rightarrow$ tree-level neutral B_s effects)
  - **$H_d - L$ distinction** (necessary for L and R-parity conservation)
  - **MSSM singlets** (NMSSM-type, ν_L^c-type, or neither)

New Matter and Z's

Field	Transformation	T_a	T_b	T_c	M_a	M_b	M_c
q_L	$(a, \bar{b})$	2	-3	0	0	$-\frac{1}{2}$	0
q_L	(a, b)	2	3	0	0	$-\frac{1}{2}$	0
u_L^c	$(\bar{a}, \bar{c})$	-1	0	-3	$\frac{1}{2}$	0	1
d_L^c	$\begin{smallmatrix}\square\\\square\end{smallmatrix}_a$	-1	0	0	$-\frac{1}{2}$	0	0
d_L^c	$(\bar{a}, c)$	-1	0	3	$-\frac{1}{2}$	0	0
H_u	(b, c)	0	1	2	0	$-\frac{1}{2}$	$-\frac{1}{3}$
H_u	$(\bar{b}, c)$	0	-1	2	0	$-\frac{1}{2}$	$-\frac{1}{3}$
H_d, L	$(b, \bar{c})$	0	1	-2	0	$\frac{1}{2}$	$\frac{1}{3}$
H_d, L	$(\bar{b}, \bar{c})$	0	-1	-2	0	$\frac{1}{2}$	$\frac{1}{3}$
e_L^c	$\square\square_c$	0	0	5	0	0	$-\frac{4}{3}$

- **Madrid 3-node embedding:** $U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c$

- $T_a = 0 \qquad T_b = \pm 2n \qquad T_c = 0 \bmod 3 \qquad$ with $\; n \in \{0, \ldots, 7\}$
  - Vector pair (H_u, H_d or H_u, L) for $n = 0 \Rightarrow$ at least one addition

- **Possible additions**

Transformation		T_a	T_b	T_c	M_a	M_b	M_c
$\square\square_a$	$(6,1)_{\frac{1}{3}}$	7	0	0	$-\frac{1}{2}$	0	0
$\overline{\square\square}_a$	$(\overline{6},1)_{-\frac{1}{3}}$	-7	0	0	$\frac{1}{2}$	0	0
$\begin{smallmatrix}\square\\\square\end{smallmatrix}_a$	$(\overline{3},1)_{\frac{1}{3}}$	-1	0	0	$-\frac{1}{2}$	0	0
$\overline{\begin{smallmatrix}\square\\\square\end{smallmatrix}}_a$	$(3,1)_{-\frac{1}{3}}$	1	0	0	$\frac{1}{2}$	0	0
$\square\square_b$	$(1,3)_0$	0	6	0	0	0	0
$\overline{\square\square}_b$	$(1,3)_0$	0	-6	0	0	0	0
$\begin{smallmatrix}\square\\\square\end{smallmatrix}_b$	$(1,1)_0$	0	-2	0	0	0	0
$\overline{\begin{smallmatrix}\square\\\square\end{smallmatrix}}_b$	$(1,1)_0$	0	2	0	0	0	0
$(\overline{b},c)$	$(1,2)_{\frac{1}{2}}$	0	-1	2	0	$-\frac{1}{2}$	$-\frac{1}{3}$
$(b,\overline{c})$	$(1,2)_{-\frac{1}{2}}$	0	1	-2	0	$\frac{1}{2}$	$\frac{1}{3}$
(b,c)	$(1,2)_{\frac{1}{2}}$	0	1	2	0	$-\frac{1}{2}$	$-\frac{1}{3}$
$(\overline{b},\overline{c})$	$(1,2)_{-\frac{1}{2}}$	0	-1	-2	0	$\frac{1}{2}$	$\frac{1}{3}$
$\square\square_c$	$(1,1)_1$	0	0	5	0	0	$-\frac{4}{3}$
$\overline{\square\square}_c$	$(1,1)_{-1}$	0	0	-5	0	0	$\frac{4}{3}$
$(a,\overline{b})$	$(3,2)_{\frac{1}{6}}$	2	-3	0	0	$-\frac{1}{2}$	0
$(\overline{a},b)$	$(\overline{3},2)_{-\frac{1}{6}}$	-2	3	0	0	$\frac{1}{2}$	0
(a,b)	$(3,2)_{\frac{1}{6}}$	2	3	0	0	$-\frac{1}{2}$	0
$(\overline{a},\overline{b})$	$(\overline{3},2)_{-\frac{1}{6}}$	-2	-3	0	0	$\frac{1}{2}$	0
$(a,\overline{c})$	$(3,1)_{-\frac{1}{3}}$	1	0	-3	$\frac{1}{2}$	0	0
$(\overline{a},c)$	$(\overline{3},1)_{\frac{1}{3}}$	-1	0	3	$-\frac{1}{2}$	0	0
(a,c)	$(3,1)_{\frac{2}{3}}$	1	0	3	$-\frac{1}{2}$	0	-1
$(\overline{a},\overline{c})$	$(\overline{3},1)_{-\frac{2}{3}}$	-1	0	-3	$\frac{1}{2}$	0	1

• 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	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$		
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\Box\Box_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\Box\Box_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	
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	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	$(\overline{a},\overline{c}),\ (\overline{3},1)_{-\frac{2}{3}}$	$\Box\Box_c,\ (1,1)_1$
1	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$
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	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\boxminus}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$

- Eight 3 and 4-node hypercharge embeddings (≤ 5 additions)
  - MSSM singlets with anomalous $U(1)$ charge; isotriplets ($Y = 0$)
  - Quasichiral 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 ($Q = (\pm 1, \pm 2)$))
  - Small number fractional charges, chiral fourth family (Landau poles), shifted fourth families:
    $(3, 2)_{-\frac{5}{6}}, (\bar{3}, 1)_{\frac{1}{3}}, (\bar{3}, 1)_{\frac{4}{3}}, (1, 2)_{-\frac{3}{2}}, (1, 3)_1$

- Quasichiral pairs
  - 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, quasistable)

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

	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 particles 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	$S_\mu H_u H_d$	$L H_u \nu_L^c$
$(-\frac{1}{3}, -\frac{1}{2}, 0)$	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

- Quivers with additional $U(1)'$ gauge symmetry
- $\lesssim 0.5$ 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?)

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
$(\overline{3},1)_{\frac{1}{3}}$	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
$(\overline{3},2)_{-\frac{1}{6}}$	34	34	34
$(\overline{3},1)_{-\frac{2}{3}}$	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
$(\overline{3},1)_{\frac{4}{3}}$	8	8	0

A TeV-Scale Z'

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

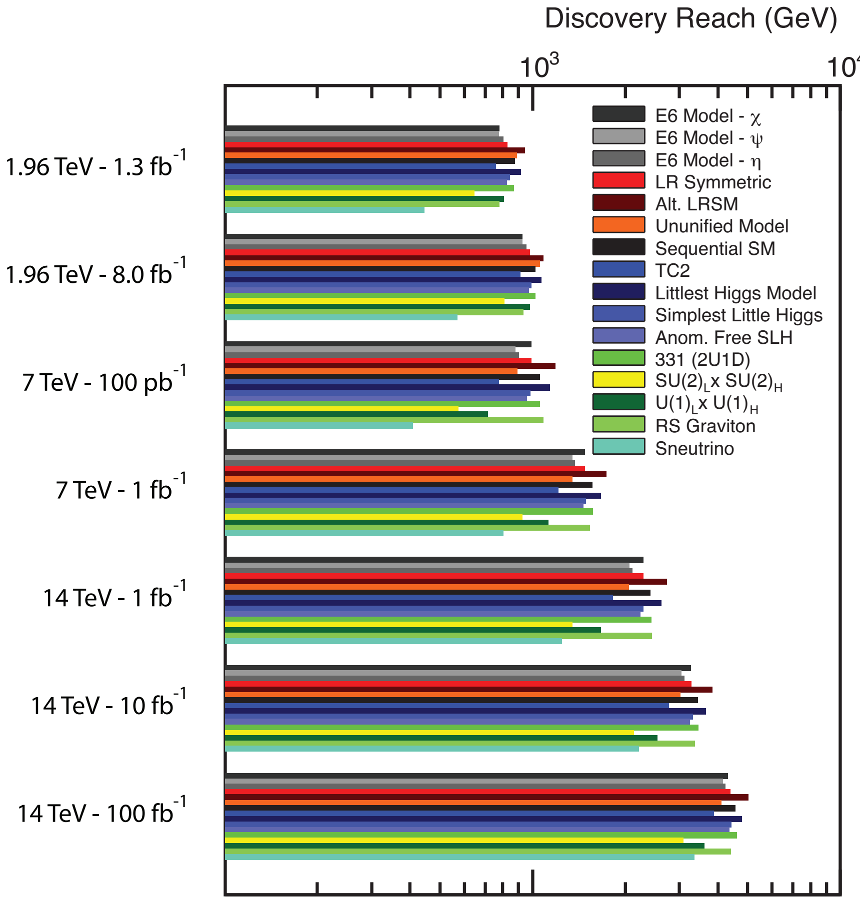
- **Strings, GUTs, DSB, little Higgs, LED often involve extra Z'**
  (harder to break $U(1)'$ factors than non-abelian: remnants)

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

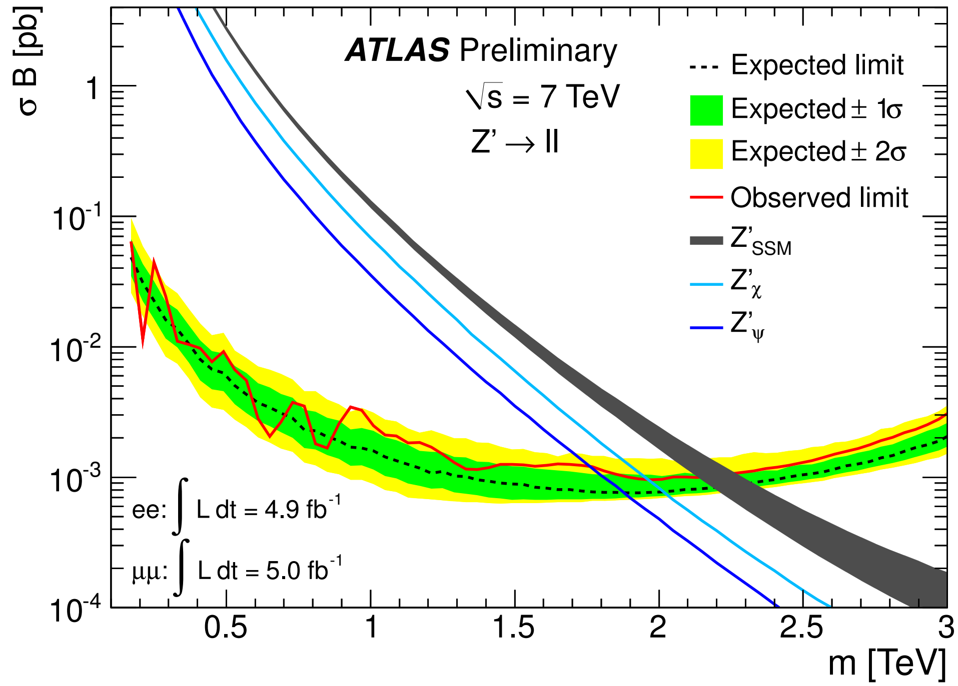
- **Discovery to $M_{Z'} \sim 5-8$ TeV at LHC, ILC,**
  $(pp \to \mu^+\mu^-, e^+e^-, q\bar{q})$ (depends on couplings, exotics, sparticles)

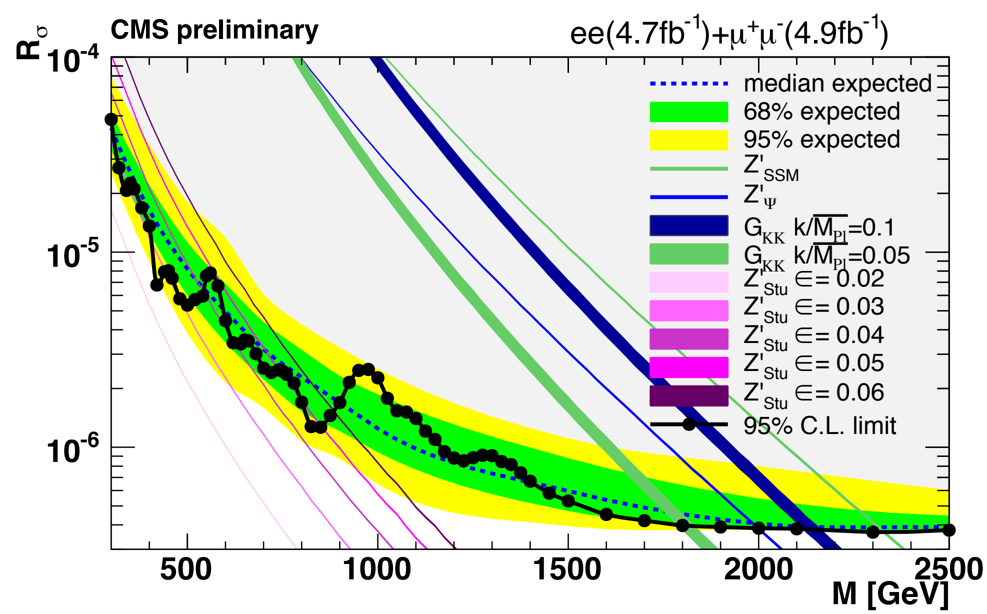
- **Diagnostics to 1-2 TeV** (asymmetries, y distributions, associated production, rare decays)

- **Light** (150-300 GeV) **leptophobic, TEV-scale** (FCNC), **or very light** (10 GeV) **Z' portal suggested by recent anomalies**



Courtesy: Steve Godfrey





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 $U(1)'$

- **Natural solution to μ problem:** $W \sim h_s S H_u H_d \to \ \mu_{eff} = h_s \langle S \rangle$ ("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 ($\to$ non-standard collider signatures)

- Extended neutralino sector
  - Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  - Enhanced cold dark matter, $g_\mu - 2$ possibilities (even small $\tan\beta$)
- 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

- **Non-universal charges: apparent CPT violation (MINOS)**
- **$Z' - \tilde{Z}'$ 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**
- **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
  - 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)

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

- Relaxed upper limits, couplings, parameter ranges (e.g., $\tan\beta = v_u/v_d$ can be close to 1), 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 mixed quasi-hidden, fractional charges**
  - **Experimental limits relatively weak**

- 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)$\to m_D \gtrsim$ 200 GeV (future: $\sim$ 1 TeV)
  - $\tilde{D} \to$ 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)

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: 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.**

Conclusions

- Combination of theoretical ideas and new experimental facilities may allow testable theory to Planck scale

- From the bottom up: there may be more at TeV scale than (minimal SUGRA) MSSM

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

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

Backup

- **MSSM hypercharge embeddings**
  (Anastasopoulos, Dijkstra, Kiritsis, Schellekens)

- **Three-node embeddings**

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

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

- **Four-node embeddings**

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

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

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