Light Z's in heterotic-string vacua and the LHC di-photon excess

PLANCK 2015: Mariano Quiros: What are the collider signatures?

With: John Rizos, NPB 895 (2015) 233; EPJC 76 (2016) 170;

Costas Kounnas, Carlo Angelantonj, Ioannis Florakis, Mirian Tsulaia

Viraf Mehta, Panos Athanasopolos, Hasan Sonmez

Johar Ashfaque, Luigi Delle Rose, Carlo Marzo

String Phenomenology 2016, Ioannina, 20 June 2016

DATA $\longrightarrow$ STANDARD MODEL

$SU(3) \times SU(2) \times U(1)_Y \longrightarrow SU(5) \longrightarrow SO(10)$

$$\left[\begin{pmatrix} \nu \\ e \end{pmatrix} + D^c_L \right] + \left[U^c_L + \begin{pmatrix} u \\ d \end{pmatrix} + E^c_L \right] + N^c_L$$

$$\bar{5} \quad + \quad 10 \quad \quad 1 \qquad \overline{} \; 16$$

STANDARD MODEL -> UNIFICATION

ADDITIONAL EVIDENCE:

Logarithmic running, proton longevity, neutrino masses

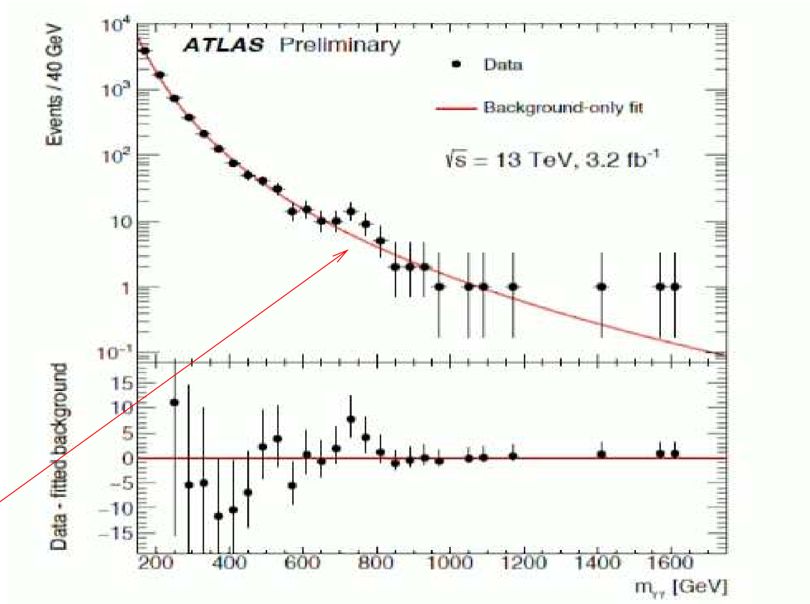
PRIMARY GUIDES:

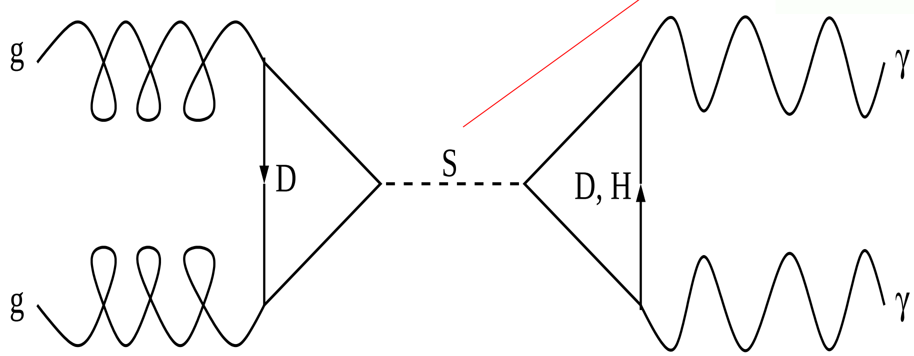
3 generations

SO(10) embedding

The DiPhoton Excess

15 December 2015





$S D \bar{D} + S H \bar{H}$

CMS also sees a peak at ~750 GeV. ATLAS favours wide width.
CMS favours narrow width.

Characteristics:

- need production cross section to be about five times bigger at 13TeV than in previous 8TeV run
- means scalar interacts with gluons, photons - not light quarks
- scalar is singlet
- mass, charge should reproduce
  - correct cross section
  - not too much gluon relative to photon (unseen jets)
  - sufficiently large photon branching ratio
  - suppression of unseen modes
  - ATLAS $\rightarrow$ potentially large width
- must interact with particles charged under color and electromagnetism
- *e.g.* massive vector–like quarks and lepton

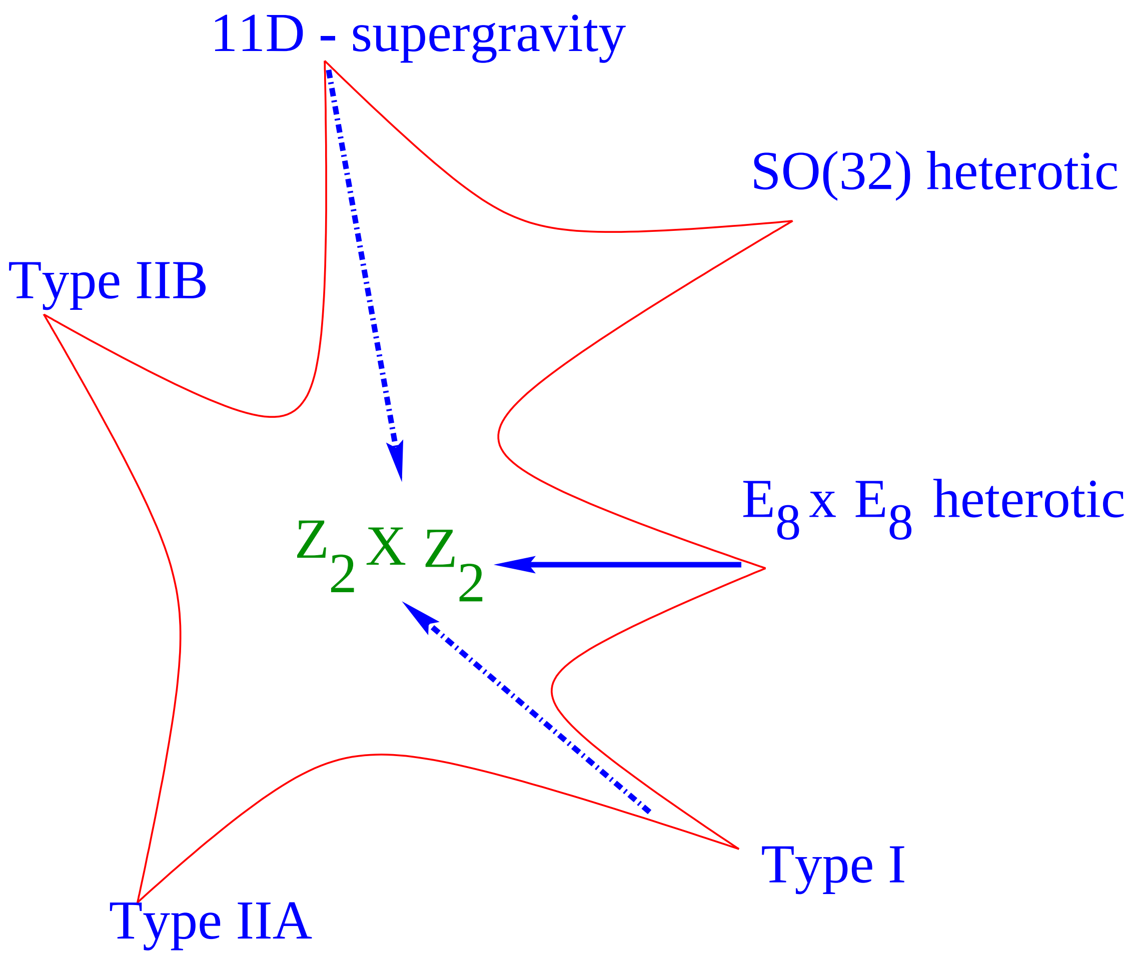
string : $\longrightarrow$ SM + light singlet & vector–like states

Realistic free fermionic models

'Phenomenology of the Standard Model and string unification'

- Minimal Superstring Standard Model — NPB 335 (1990) 347 (with Nanopoulos & Yuan)
- Top quark mass $\sim$ 175–180GeV — PLB 274 (1992) 47
- Generation mass hierarchy — NPB 407 (1993) 57
- CKM mixing — NPB 416 (1994) 63 (with Halyo)
- Stringy seesaw mechanism — PLB 307 (1993) 311 (with Halyo)
- Gauge coupling unification — NPB 457 (1995) 409 (with Dienes)
- Proton stability — NPB 428 (1994) 111
- Squark degeneracy — NPB 526 (1998) 21 (with Pati)
- Moduli fixing — NPB 728 (2005) 83
- Classification & Exophobia — 2003 – $\cdots$ (with Nooij, Assel, Christodoulides, Kounnas, Rizos & Sonmez)

Point, String, Membrane ....



Other approaches

Geometrical

Greene, Kirklin, Miron, Ross (1987)
Donagi, Ovrut, Pantev, Waldram (1999)
Blumenhagen, Moster, Reinbacher, Weigand (2006)
Heckman, Vafa (2008)
....

Orbifolds

Ibanez, Nilles, Quevedo (1987)
Bailin, Love, Thomas (1987)
Kobayashi, Raby, Zhang (2004)
Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter (2007)
Blaszczyk, Groot–Nibbelink, Ruehle, Trapletti, Vaudrevange (2010)
....

Other CFTs

Gepner (1987)
Schellekens, Yankielowicz (1989)
Gato–Rivera, Schellekens (2009)
....

Orientifolds

Cvetic, Shiu, Uranga (2001)
Ibanez, Marchesano, Rabadan (2001)
Kiristis, Schellekens, Tsulaia (2008)
....

Some references on: 'Z' in free fermionic models'

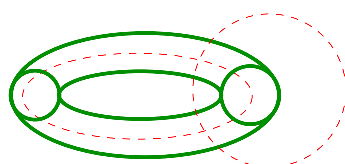
- $\frac{3}{2}U(1)_{B-L} - 2U(1)_R \in SO(10)$ @ $1TeV$ MPL A6 (1991) 61 (with Nanopoulos)
- But $m_t = m_{\nu_\tau}$ & $1TeV$ $Z' \Rightarrow$ $m_{\nu_\tau} \approx 10MeV$ PLB 245 (1990) 435
- Pati – 1996 $U(1)s \notin SO(10)$ $\rightarrow$ $\tau_{\rm P}$ & M_{ν_L} PLB 388 (1996) 532
- Pati's $U(1)$s broken at $M_{\rm string}$ PLB 499 (2001) 147
- String derived anomaly free Z' PLB EPJC 53 (2008) 421 (with Coriano & Guzzi)
- String inspired collider Z' PRD 78 (2008) 015012 (with Coriano & Guzzi)
- String inspired anomaly free model PRD 84 (2011) 086006 (with Mehta)
- Gauge coupling constraints ... (with Mehta)
- Z' string derived model ... (with Rizos)

Free Fermionic Construction

Left-Movers: $\psi^{\mu}_{1,2}, \quad \chi_i, \quad y_i, \; \omega_i \quad (i = 1, \cdots, 6)$

Right-Movers

$$\bar{\phi}_{A=1,\cdots,44} = \begin{cases} \bar{y}_i \;,\; \bar{\omega}_i & i = 1, \cdots, 6 \\ \\ \bar{\eta}_i & i = 1, 2, 3 \\ \bar{\psi}_{1,\cdots,5} & \\ \bar{\phi}_{1,\cdots,8} & \end{cases}$$



$V \longrightarrow V \qquad\qquad f \longrightarrow -e^{i\pi\alpha(f)} f$

$$Z = \sum_{\substack{all \; spin \\ structures}} c\binom{\vec{\alpha}}{\vec{\beta}} \, Z\binom{\vec{\alpha}}{\vec{\beta}}$$

Models $\longleftrightarrow$ Basis vectors $+$ one–loop phases

$E_6 \to SO(10) \times U(1)_A \implies U(1)_A$ is anomalous!

$\implies U(1)_A \notin$ low scale $U(1)_{Z'}$

On the other hand ....

$$\sin^2\theta_W(M_Z)\ ,\ \alpha_s(M_Z) \implies U(1)_{Z'} \in E_6$$

light Z' heterotic–string model : AEF, John Rizos, NPB895 (2015) 233

Observable gauge group: $SO(6) \times SO(4) \times U(1)_{1,2,3}$

$U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3 \in E_6$ is anomaly free

Classification of fermionic $Z_2 \times Z_2$ orbifolds

Basis vectors:

$$
\begin{aligned}
1 &= \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\} \\
S &= \{\psi^\mu, \chi^{1,\dots,6}\}, \\
z_1 &= \{\bar{\phi}^{1,\dots,4}\}, \\
z_2 &= \{\bar{\phi}^{5,\dots,8}\}, \\
e_i &= \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6, \qquad N = 4 \text{ Vacua} \\
b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\}, \qquad N = 4 \to N = 2 \\
b_2 &= \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\}, \qquad N = 2 \to N = 1 \\
\alpha &= \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\} \qquad \& \quad SO(10) \to SO(6) \times SO(4) \times \cdots \\
\beta &= \{\bar{\psi}^{1,\cdots,5} = \tfrac{1}{2}, \cdots\} \qquad \& \quad SO(10) \to SU(5) \times U(1) \times \cdots
\end{aligned}
$$

Independent phases $c\begin{bmatrix} v_i \\ v_j \end{bmatrix} = \exp[i\pi(v_i|v_j)]$: upper block

$$
\begin{array}{c}
\\ 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ z_1 \\ z_2 \\ b_1 \\ b_2 \\ \alpha
\end{array}
\begin{array}{c}
\begin{array}{ccccccccccccc}
1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & z_1 & z_2 & b_1 & b_2 & \alpha
\end{array}
\\
\begin{pmatrix}
-1 & -1 & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 \\
 & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
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 & & & & & & & & & \pm & \pm & \pm & \pm \\
 & & & & & & & & & & \pm & \pm & \pm \\
 & & & & & & & & & & & \pm & \pm \\
 & & & & & & & & & & & -1 & \pm \\
 & & & & & & & & & & & &
\end{pmatrix}
\end{array}
$$

A priori 66 independent coefficients $\rightarrow$ 2^{66} distinct vacua

The twisted matter spectrum:

$$B^1_{\ell^1_3\ell^1_4\ell^1_5\ell^1_6} = S + b_1 + \ell^1_3 e_3 + \ell^1_4 e_4 + \ell^1_5 e_5 + \ell^1_6 e_6$$

$$B^2_{\ell^2_1\ell^2_2\ell^2_5\ell^2_6} = S + b_2 + \ell^2_1 e_1 + \ell^2_2 e_2 + \ell^2_5 e_5 + \ell^2_6 e_6$$

$$B^3_{\ell^3_1\ell^3_2\ell^3_3\ell^3_4} = S + b_3 + \ell^3_1 e_1 + \ell^3_2 e_2 + \ell^3_3 e_3 + \ell^3_4 e_4 \qquad l^j_i = 0, 1$$

sectors $B^i_{pqrs} \quad \rightarrow \quad 16$ or $\overline{16}$ of $SO(10)$ with multiplicity $(1, 0, -1)$

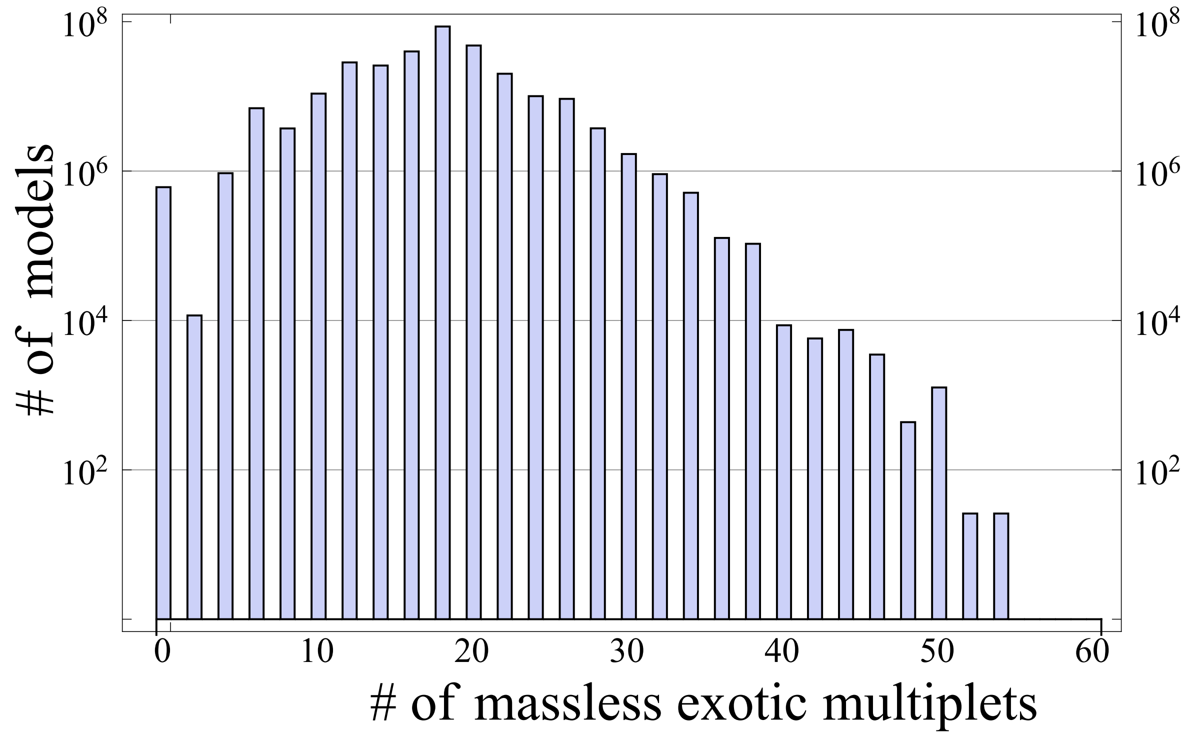
$$B^i_{pqrs} + x \quad \rightarrow \quad 10 \quad \text{of } SO(10) \text{ with multiplicity } (1, 0)$$

$x = \{\bar{\psi}^{1,\cdots,5}, \bar{\eta}^1, \bar{\eta}^2, \bar{\eta}^3\}$ $\qquad x -$ map $\leftrightarrow$ spinor–vector map

Algebraic formulas for $S = \sum_{i=1}^{3} S^{(i)}_+ - S^{(i)}_-$ and $V = \sum_{i=1}^{3} V^{(i)}$

Pati–Salam class: with Assel, Christodoulides, Kounnas, Rizos

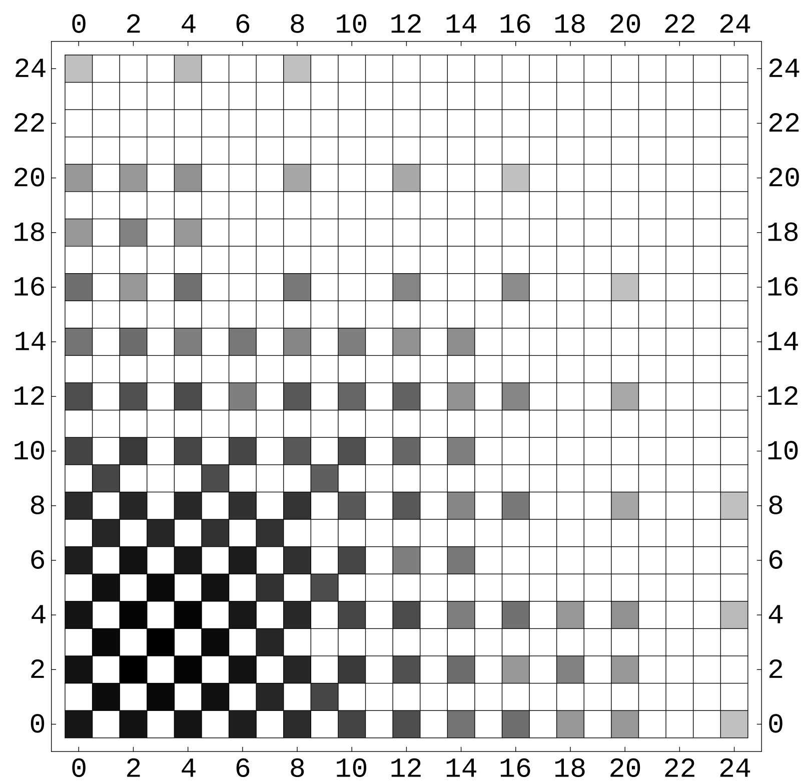
RESULTS: of random search of over 10^{11} vacua



Number of 3-generation models versus total number of exotic multiplets

Spinor–vector duality:

Invariance under exchange of $\#(16+\overline{16}) \;\; <-> \;\; \#(10)$



Symmetric under exchange of rows and columns

$$E_6 \;\; : \qquad 27 = 16 + 10 + 1 \qquad \overline{27} = \overline{16} + 10 + 1$$

Self-dual: $\#(16+\overline{16}) \;\; = \;\; \#(10)$ without E_6 symmetry

light Z' heterotic–string model $c\begin{bmatrix} v_i \\ v_j \end{bmatrix} = \exp[i\pi(v_i|v_j)]$:

$$
(v_i|v_j) \ = \ \begin{array}{c} \\ 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ b_1 \\ b_2 \\ z_1 \\ z_2 \\ \alpha \end{array}
\begin{array}{c} \begin{array}{ccccccccccccc} 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & b_1 & b_2 & z_1 & z_2 & \alpha \end{array} \\
\left(\begin{array}{ccccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1
\end{array}\right) \end{array}
$$

Observable gauge group: $SO(6) \times SO(4) \times U(1)_{1,2,3}$

$U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3$ is anomaly free

sector	field	$SU(4)\times SU(2)_L\times SU(2)_R$	$U(1)_1$	$U(1)_2$	$U(1)_3$	$U(1)_\zeta$
$S+b_1$	$\bar{F}_{1R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	1/2	0	0	1/2
$S+b_1+e_3+e_5$	F_{1R}	$(\mathbf{4},\mathbf{1},\mathbf{2})$	1/2	0	0	1/2
$S+b_2$	F_{1L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	1/2	0	1/2
$S+b_2+e_1+e_2+e_5$	F_{2L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	1/2	0	1/2
$S+b_2+e_1$	$\bar{F}_{2R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	1/2	0	1/2
$S+b_2+e_2+e_5$	$\bar{F}_{3R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	1/2	0	1/2
$S+b_3+e_1+e_2$	F_{3L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	0	1/2	1/2
$S+b_3+e_2$	$\bar{F}_{4R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	0	1/2	1/2
$S+b_3+x$	h_1	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	$-1/2$	0	-1
$S+b_2+x+e_5$	h_2	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	0	$-1/2$	-1
$S+b_2+x+e_1+e_2$	h_3	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	0	$-1/2$	-1
$S+b_3+x+e_1$	D_4	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	$-1/2$	0	-1
	χ_1^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1/2	1	+2
	χ_1^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1/2	-1	0
	$\zeta_a, a=2,3$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	$-1/2$	0	0
	$\bar{\zeta}_a, a=2,3$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	1/2	0	0
$S+b_2+x+e_1+e_5$	D_5	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	0	$-1/2$	-1
	χ_2^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1	1/2	+2
	χ_2^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	-1	1/2	0
	$\zeta_a, a=4,5$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	0	$-1/2$	0
	$\bar{\zeta}_a, a=4,5$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	0	1/2	0
$S+b_2+x+e_2$	D_6	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	0	$-1/2$	-1
	χ_3^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1	1/2	+2
	χ_3^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	-1	1/2	0
	$\zeta_a, a=6,7$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	0	$-1/2$	0
	$\bar{\zeta}_a, a=6,7$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	0	1/2	0
$S+b_1+x+e_3$	$\bar{D}_6$	$(\mathbf{6},\mathbf{1},\mathbf{1})$	0	1/2	1/2	+1
	$\bar{\chi}_4^+$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	-1	$-1/2$	$-1/2$	-2
	$\bar{\chi}_4^-$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1	$-1/2$	$-1/2$	0
	$\zeta_a, a=8,9$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	$-1/2$	0
	$\bar{\zeta}_a, a=8,9$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	1/2	0
$S+b_1+x+e_5$	D_7	$(\mathbf{6},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1
	χ_5^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1	1/2	1/2	+2
	χ_5^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	-1	1/2	1/2	0
	$\zeta_a, a=10,11$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	$-1/2$	0
	$\bar{\zeta}_a, a=10,11$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	1/2	0
$S+b_3+x+e_2+e_3$	ζ_1	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	$-1/2$	0	0
	$\bar{\zeta}_1$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	1/2	0	0
$S+b_1+x+e_3+e_4+e_6$	ϕ_1	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	1/2	+1
	$\bar{\phi}_1$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1
$S+b_1+x+e_4+e_5+e_6$	ϕ_2	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	1/2	+1
	$\bar{\phi}_2$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1

Table 1: *Observable twisted matter spectrum and* $SU(4)\times SU(2)_L\times SU(2)_R\times U(1)^3$ *quantum numbers.*

The chiral spectrum is self–dual under spinor–vector duality

maintains the E_6 embedding $\Rightarrow$ $U(1)_\zeta$ is anomaly free

three generations + heavy and light higgs + $\lambda_t \sim 1$

$$U(1)_{Z'} \; = \; \tfrac{1}{5}\, U(1)_C \; - \; \tfrac{1}{5}\, U(1)_L - U_\zeta$$

$Z' \Rightarrow$ Additional matter at the Z' breaking scale

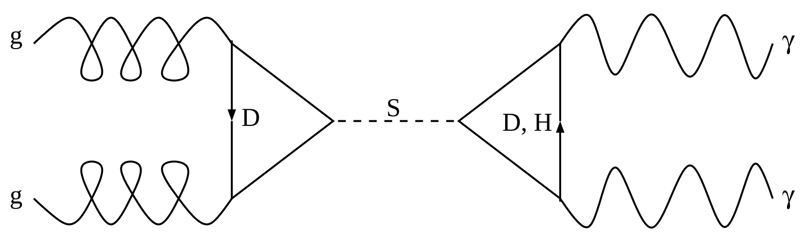
Exotic $SO(10)$ singlets with non–standard $U(1)_\zeta$ charges

$\Rightarrow$ Natural Wilsonian dark–matter candidates

Z' at the LHC Heavy Higgs $\langle \mathcal{N} \rangle \sim M_{\rm String}$ $\rightarrow$ high seesaw $\rightarrow$ Z'

Field	$SU(3)_C$	$\times SU(2)_L$	$U(1)_Y$	$U(1)_{Z'}$
Q_L^i	3	2	$+\frac{1}{6}$	$-\frac{2}{5}$
u_L^i	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{2}{5}$
d_L^i	$\bar{3}$	1	$+\frac{1}{3}$	$-\frac{4}{5}$
e_L^i	1	1	$+1$	$-\frac{2}{5}$
L_L^i	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
D^i	3	1	$-\frac{1}{3}$	$+\frac{4}{5}$
$\bar{D}^i$	$\bar{3}$	1	$+\frac{1}{3}$	$+\frac{6}{5}$
H^i	1	2	$-\frac{1}{2}$	$+\frac{6}{5}$
$\bar{H}^i$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
S^i	1	1	0	-2

di–photon events



AEF and John Rizos, EPJC76 (2016) 170, and references therein

Gauge Coupling Unification

$$\frac{1}{\alpha_X} = \frac{1}{k_i \alpha_i(M_Z)} - \frac{b_i^{Z'}}{2\pi} \ln \frac{M_X}{M_Z} \qquad \longrightarrow \qquad Z' \quad M_X \to M_Z$$

$$+ \frac{b_{ij}^{\text{L.T.}}}{2\pi} \ln \frac{M_j}{M_Z} \qquad \longrightarrow \qquad \text{Light thresholds}$$

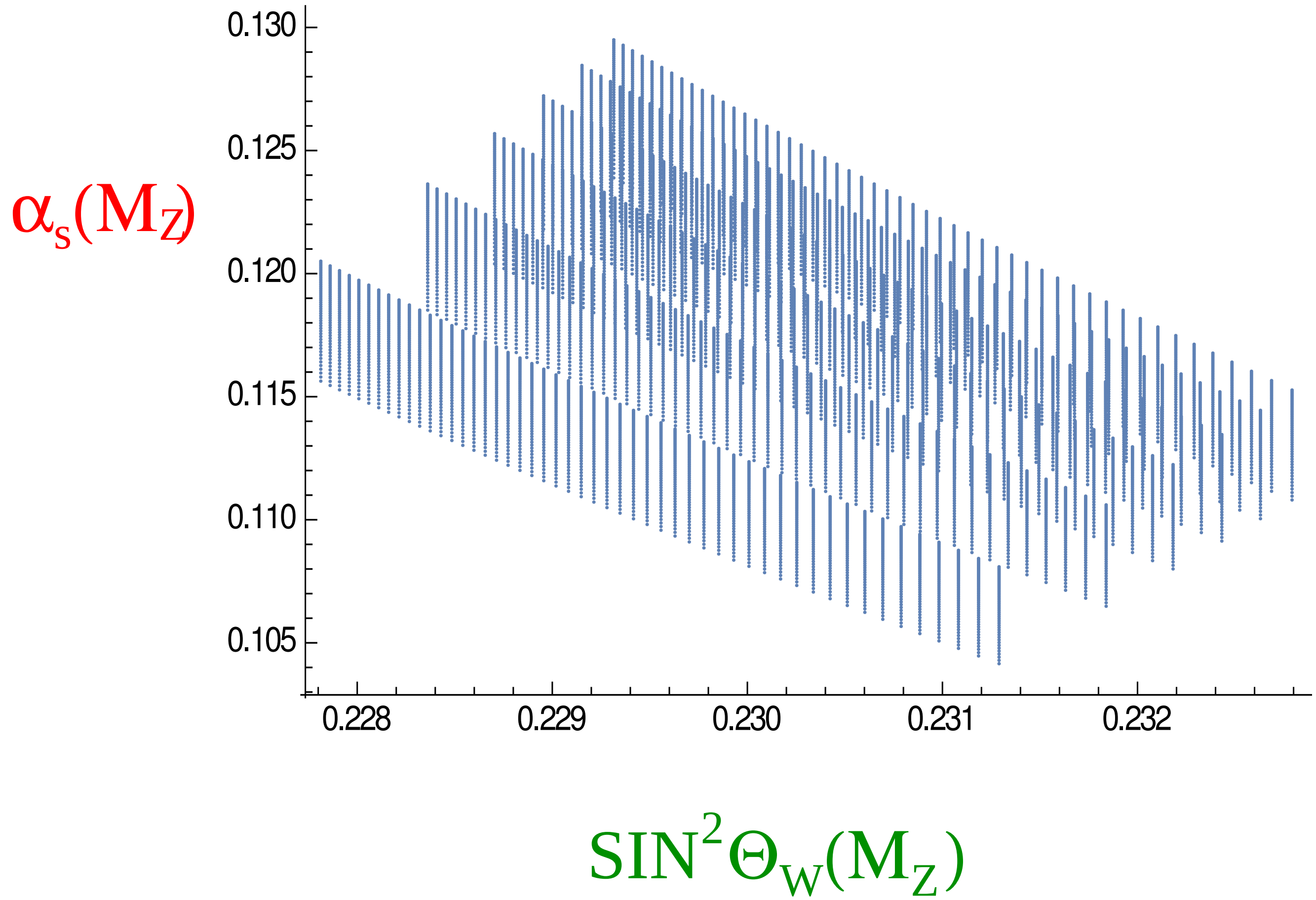
$$+ \quad \Delta_i \qquad \longrightarrow \qquad \text{other corrections}$$

Solve the one–loop equations for $\sin^2\theta_W(M_Z)|_{\overline{MS}}$ and $\frac{1}{a_3(M_Z)}|_{\overline{MS}}$

$$b_1^{Z'} = b_1^{\text{MSSM}} + 3 \quad ; \quad b_2^{Z'} = b_2^{\text{MSSM}} + 3 \quad ; \quad b_3^{Z'} = b_1^{\text{MSSM}} + 3$$

$$\delta \sin^2(\theta_W)_{light} = \frac{5\alpha}{16\pi}\left(\quad \cdots \quad + \frac{6}{5} \log \frac{M_D}{M_Z} - \frac{6}{5} \log \frac{M_H}{M_Z} \right)$$

$$\delta(\alpha_3^{-1})_{light} = \frac{1}{2\pi}\left(\quad \cdots \quad - \frac{9}{4} \log \frac{M_D}{M_Z} + \frac{9}{4} \log \frac{M_H}{M_Z} \right)$$



0.130
0.125
0.120
0.115
0.110
0.105
0.228
0.229
0.230
0.231
0.232
$\alpha_s(M_Z)$
$SIN^2\Theta_W(M_Z)$

Conclusions

- DATA $\longrightarrow$ HIGH SCALE UNIFICATION

- STRING CONSISTENCY REQUIRES EXTRA $U(1)$s

- $\longrightarrow$? Light Z' ?

  motivated by proton stability; μ–term ...

  Hard to implement $M_{Z'} \sim \mathrm{TeV}$ in heterotic string constructions ...

- di-photon events $\leftrightarrow$ fit naturally in Z' model

- $\Rightarrow$ Additional matter, dark matter candidates ...

- Can do di–photon without light Z' but ...