Light Z' in heterotic string models

Motivation - proton stability; μ–parameter; vector bosons exist ...

Constraints

Constructions

With: Claudio Coriano, Marco Guzzi

Viraf Mehta

John Rizos, Kyriakos Tamvakis

Bethe workshop on Strings and Unification, Badhonnef, 1–5 October 2012

DATA $\longrightarrow$ STANDARD MODEL

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

$$\left[\begin{pmatrix} \nu \\ e \end{pmatrix} + D_L^c \right] + \left[U_L^c + \begin{pmatrix} u \\ d \end{pmatrix} + E_L^c \right] + N_L^c$$

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

STANDARD MODEL -> UNIFICATION

ADDITIONAL EVIDENCE:

Logarithmic running, proton longevity, neutrino masses

PRIMARY GUIDES:

3 generations

SO(10) embedding

Realistic free fermionic models

'Phenomenology of the Standard Model and string unification'

- 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)
- Minimal Superstring Standard Model — NPB 335 (1990) 347 (with Nanopoulos & Yuan)
- Moduli fixing — NPB 728 (2005) 83
- Exophobia — PLB 683 (2010) 306 (with Assel, Christodoulides, Kounnas & Rizos)

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'

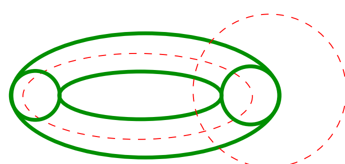
- $\frac{3}{2}U(1)_{B-L} - 2U(1)_R \in SO(10)$ @ $1TeV$ — MPL A6 (1991) 61 (with Nanopoulos)
- But $m_t = m_{\nu_\tau}$ & $1TeV$ $Z' \Rightarrow$ $m_{\nu_\tau} \approx 10MeV$ — PLB 245 (1990) 435
- Pati – 1996 $U(1)s \notin SO(10)$ $\rightarrow$ $\tau_{\rm P}$ & M_{ν_L} — PLB 388 (1996) 532
- Pati's $U(1)$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' in $SU(6) \times SU(2)$ string models ... — (with Rizos & Tamvakis)

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

Away from the free fermionic point: $Z_2 \times Z_2$ orbifolds

$$Z = \int \frac{d^2\tau}{\tau_2^2} \frac{\tau_2^{-1}}{\eta^{12}\bar{\eta}^{24}} \frac{1}{2^3} \left(\sum (-)^{a+b+ab} \vartheta \begin{bmatrix} a \\ b \end{bmatrix} \vartheta \begin{bmatrix} a+h_1 \\ b+g_1 \end{bmatrix} \vartheta \begin{bmatrix} a+h_2 \\ b+g_2 \end{bmatrix} \vartheta \begin{bmatrix} a+h_3 \\ b+g_3 \end{bmatrix} \right)_{\psi^\mu,}$$

$$\times \left(\frac{1}{2} \sum_{\epsilon,\xi} \bar{\vartheta} \begin{bmatrix} \epsilon \\ \xi \end{bmatrix}^5 \bar{\vartheta} \begin{bmatrix} \epsilon+h_1 \\ \xi+g_1 \end{bmatrix} \bar{\vartheta} \begin{bmatrix} \epsilon+h_2 \\ \xi+g_2 \end{bmatrix} \bar{\vartheta} \begin{bmatrix} \epsilon+h_3 \\ \xi+g_3 \end{bmatrix} \right)_{\bar{\psi}^{1\ldots5},\bar{\eta}^{1,2,3}}$$

$$\times \left(\frac{1}{2} \sum_{H_1,G_1} \frac{1}{2} \sum_{H_2,G_2} (-)^{H_1G_1+H_2G_2} \bar{\vartheta} \begin{bmatrix} \epsilon+H_1 \\ \xi+G_1 \end{bmatrix}^4 \bar{\vartheta} \begin{bmatrix} \epsilon+H_2 \\ \xi+G_2 \end{bmatrix}^4 \right)_{\bar{\phi}^{1\ldots8}}$$

$$\times \left(\sum_{s_i,t_i} \Gamma_{6,6} \begin{bmatrix} h_i|s_i \\ g_i|t_i \end{bmatrix} \right)_{(y\omega\bar{y}\bar{\omega})^{1\ldots6}} \times e^{i\pi\Phi(\gamma,\delta,s_i,t_i,\epsilon,\xi,h_i,g_i,H_1,G_1,H_2,G_2)}$$

$$\Gamma_{1,1}\left[{}^h_g\right] = \frac{R}{\sqrt{\tau_2}} \sum_{\tilde{m},n} \exp\left[-\frac{\pi R^2}{\tau_2} \left| (2\tilde{m}+g) + (2n+h)\,\tau \right|^2 \right]$$

The NAHE set:

$$1 \;=\; \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\}$$

$$S \;=\; \{\psi^\mu, \chi^{1,\dots,6}\}, \qquad N=4 \text{ Vacua}$$

$$b_1 \;=\; \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^{1}, \bar{\psi}^{1,\dots,5}\}, \qquad N=4 \rightarrow N=2$$

$$b_2 \;=\; \{\chi^{12}, \chi^{56}, y^{12}, \omega^{56} | \bar{y}^{12}, \bar{\omega}^{56}, \bar{\eta}^{2}, \bar{\psi}^{1,\dots,5}\}, \qquad N=2 \rightarrow N=1$$

$$b_3 \;=\; \{\chi^{12}, \chi^{34}, \omega^{12}, \omega^{34} | \bar{\omega}^{12}, \bar{\omega}^{34}, \bar{\eta}^{3}, \bar{\psi}^{1,\dots,5}\}, \qquad N=2 \rightarrow N=1$$

$Z_2 \times Z_2$ orbifold compactification

$\Longrightarrow$ Gauge group $SO(10) \times SO(6)^{1,2,3} \times E_8$

beyond the NAHE set

Add $\{\alpha, \beta, \gamma\}$

number of generations is reduced to three

$$SO(10) \longrightarrow SU(3) \times SU(2) \times U(1)_{T_{3_R}} \times U(1)_{B-L}$$

$$U(1)_Y = \frac{1}{2}(B-L) + T_{3_R} \in SO(10) \, !$$

$$SO(6)^{1,2,3} \longrightarrow U(1)^{1,2,3} \times U(1)^{1,2,3}$$

Towards String Predictions

1. Low energy supersymmetry

   Specific SUSY breaking patterns $\longrightarrow$ Collider implications

2. Additional (non–GUT) gauge bosons

   Proton Stability and low–scale Z' $\longrightarrow$ Collider signatures

3. Exotic matter

   In realistic string models

   Unifying gauge group $\Rightarrow$ broken by “Wilson lines”.

   $\Rightarrow$ non–GUT physical states.

   $\Rightarrow$ Meta-stable heavy string relics

   $\rightarrow$ Dark Mater ; UHECR candidates

Proton stability and superstring Z'

Standard Model: $(SU321) \oplus (Q\ L\ U\ D\ E\ N) \oplus (h)$:

Effective renormalizable QFT below a cutoff

baryon and lepton numbers protected by accidental global symmetries

Non-renormalizable operators suppressed by cutoff M

B & L numbers violating operators

Dimension six: $QQQL\frac{1}{M^2}$ $\Rightarrow$ $M \sim 10^{16} GeV$

supersymmetry:

Dimension four: $\eta_1 QLD \ \& \ \eta_2 UDD$ $\Rightarrow$ $(\eta_1 \cdot \eta_2 \leq 10^{-24})$

Dimension five: $\lambda QQQL\frac{1}{M}$ $\Rightarrow$ $(\frac{\lambda}{M}) \leq 10^{-26}$

Appealing Proposition: Low scale gauged $U(1)$ symmetry

Additional Facts

Standard Model: $\longrightarrow$ Unification $\longleftrightarrow$ $SO(10)$

Dimension four: $16^4 \Rightarrow \eta_1' UDD\frac{\langle N\rangle}{M} + \eta_2' QLD\frac{\langle N\rangle}{M}$

$+$ ... dimension five ; dimension six

left–handed neutrino masses: $M_{\nu_L} \approx M_{\rm Up}\left(\frac{M_{\rm weak}}{M_{\langle N\rangle}}\right)^2$

Fermion masses: $\lambda_{ij}^{\rm Up} Q^i U^j \bar{h}$; $\lambda_{ij}^{\rm Down} Q^i D^j h$; $\lambda_{ij}^{\rm CLepton} L^i E^j h$;

Flavour universality

Freedom from anomalies

What can we learn from string constructions?

Extra $U(1)$'s beyond the Standard Model

e.g. PLB 278 (1992) 131 $\longrightarrow$ seven extra $U(1)$'s

$$U(1)_{Z'} = \frac{B-L}{2} - \frac{2}{3} T_{3_R}$$

The $U(1)$ combinations

$$U_A = \frac{1}{\sqrt{15}}(2(U_1 + U_2 + U_3) - (U_4 + U_5 + U_6))$$

$$U_\chi = \frac{1}{\sqrt{15}}(U_1 + U_2 + U_3 + 2U_4 + 2U_5 + 2U_6)$$

$$U_{12} = \frac{1}{\sqrt{2}}(U_1 - U_2) \quad , \quad U_\psi = \frac{1}{\sqrt{6}}(U_1 + U_2 - 2U_3),$$

$$U_{45} = \frac{1}{\sqrt{2}}(U_4 - U_5) \quad , \quad U_\rho = \frac{1}{\sqrt{6}}(U_4 + U_5 - 2U_6)$$

Pati, PLB388 (1996) 532; $U(1)_\psi$ in conjuction with $U(1)_{B-L}$ or $U(1)_\chi$ provides adequate protection as well as allowing light neutrino masses

PLB499 (2001) 147; the extra $U(1)$s are broken at high scale

Patterns of $SO(10)$ symmetry breaking

The $SO(10) \to$ subgroup $b(\bar{\psi}^{1\cdots5}_{\frac{1}{2}})$:

1. $b\{\bar{\psi}^{1\cdots5}_{\frac{1}{2}}\ \bar{\eta}^1\ \bar{\eta}^2\ \bar{\eta}^3\} = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\} \Rightarrow SU(5) \times U(1)\ \ U(1)\ U(1)\ U(1)$
2. $b\{\bar{\psi}^{1\cdots5}_{\frac{1}{2}}\ \bar{\eta}^1\ \bar{\eta}^2\ \bar{\eta}^3\} = \{\ 11100\ 000\ \} \Rightarrow SO(6) \times SO(4)\ U(1)\ U(1)\ U(1)$

$$(1. + 2.)\ \Rightarrow\ SO(10)\ \to SU(3)_C \times SU(2)_L \times U(1)_C \times U(1)_L$$

$$SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

2. $b\{\bar{\psi}^{1\cdots5}_{\frac{1}{2}}\bar{\eta}^1\ \bar{\eta}^2\ \bar{\eta}^3\} = \{\ 11100000\ \} \Rightarrow SO(6) \times SO(4)\ U(1)\ U(1)\ U(1)$
3. $b\{\bar{\psi}^{1\cdots5}_{\frac{1}{2}}\ \bar{\eta}^1\ \bar{\eta}^2\ \bar{\eta}^3\} = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}00\frac{1}{2}\frac{1}{2}\frac{1}{2}\} \Rightarrow$

$$SU(\ 3\ )_C \times U(1)_C \times SU(2)_L \times SU(2)_R\ U(1)\ U(1)\ U(1)$$

$U(1)$ matter charges

in cases 1. 2.

$$\Longrightarrow \qquad Q_{U(1)_j}(16 = \{Q, L, U, D, E, N\}) \;=\; +\frac{1}{2}$$

$\Longrightarrow$ the $U(1)_{1,2,3}$ are anomalous

In the LRS model of case 3.

$$\Longrightarrow \qquad Q_{U(1)_j}(Q_L, L_L) \;=\; -\frac{1}{2}$$

$$Q_{U(1)_j}(Q_R = \{U, D\}, L_R = \{E, N\}) \;=\; +\frac{1}{2}$$

$\Longrightarrow$ the $U(1)_{1,2,3}$ are anomaly free

The $U(1)_\zeta$ combination $U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3$ is :

a. family universal

b. anomaly free

The Baryon number violating terms :

$$Q_L Q_L Q_L L_L \rightarrow QQQL$$
$$Q_R Q_R Q_R L_R \rightarrow \{UDDN, UUDE\}$$

are forbidden

The Lepton number violating terms :

$$Q_L Q_R L_L L_R \rightarrow QDLN$$
$$L_L L_L L_R L_R \rightarrow LLEN$$

are allowed

The fermion mass terms:

$$Q_L Q_R h \quad \text{and} \quad L_L L_R h \quad \text{and} \quad N N \bar{N}_H \bar{N}_H \ .$$

are allowed

STRING DERIVED LEFT-RIGHT SYMMETRIC MODEL

	ψ^μ	χ^{12}	χ^{34}	χ^{56}	$y^{3,...,6}$	$\bar{y}^{3,...,6}$	$y^{1,2},\omega^{5,6}$	$\bar{y}^{1,2},\bar{\omega}^{5,6}$	$\omega^{1,...,4}$	$\bar{\omega}^{1,...,4}$	$\bar{\psi}^{1,...,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^{1,...,8}$
1	1	1	1	1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1	1	1	1,...,1
S	1	1	1	1	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0	0	0	0,...,0
b_1	1	1	0	0	1,...,1	1,...,1	0,...,0	0,...,0	0,...,0	0,...,0	1,...,1	1	0	0	0,...,0
b_2	1	0	1	0	0,...,0	0,...,0	1,...,1	1,...,1	0,...,0	0,...,0	1,...,1	0	1	0	0,...,0
b_3	1	0	0	1	0,...,0	0,...,0	0,...,0	0,...,0	1,...,1	1,...,1	1,...,1	0	0	1	0,...,0

	ψ^μ	χ^{12}	χ^{34}	χ^{56}	y^3y^6	$y^4\bar{y}^4$	$y^5\bar{y}^5$	$\bar{y}^3\bar{y}^6$	$y^1\omega^5$	$y^2\bar{y}^2$	$\omega^6\bar{\omega}^6$	$\bar{y}^1\bar{\omega}^5$	$\omega^2\omega^4$	$\omega^1\bar{\omega}^1$	$\omega^3\bar{\omega}^3$	$\bar{\omega}^2\bar{\omega}^4$	$\bar{\psi}^{1,...,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^{1,...}$
α	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	1 1 1 0 0	0	0	0	1 1 1 1
β	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0	1	1 1 1 0 0	0	0	0	1 1 0 0
γ	0	0	0	0	0	1	0	1	0	1	0	1	1	0	0	0	$\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ 0 0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1 $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$

Gerald Cleaver, AEF and Christopher Savage, PRD 63:066001,2001.

3 generations;

3 untwisted Higgs bi–doublets;

Fermion mass terms arise from $N = 3$ and $N = 5$ superpotential terms

.

.

.

Leptophobic Z' (PLB388 (1996) 524; arXiv:1106.5422 with Viraf Mehta)

In the LRS models

$$U(1)_{B'} = \frac{1}{3}U_C - U_1 - U_2 - U_3$$

$$Q_{B'}(L_L) = -\frac{1}{2} + \frac{1}{2} = 0 \qquad Q_{B'}(L_R) = +\frac{1}{2} - \frac{1}{2} = 0$$

$$Q_{B'}(Q_L) = +\frac{1}{2} + \frac{1}{2} = +1 \qquad Q_{B'}(Q_R) = -\frac{1}{2} - \frac{1}{2} = -1$$

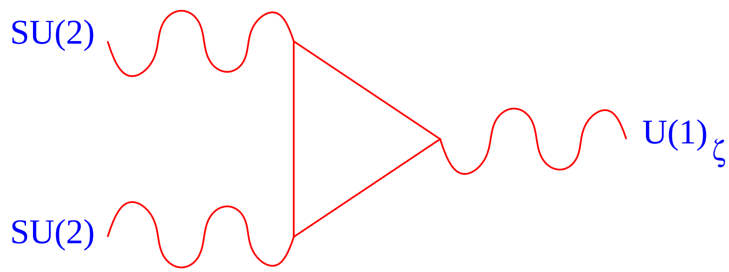
$$\longrightarrow$$

A Family Universal Anomaly Free Leptophobic $U(1)$

String inspired Z' model (with Viraf Mehta (prelimenary))

- String scale: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_C \times U(1)_\zeta$

- Chiral matter states: $Q_L,\ Q_R = U + D,\ L_L,\ L_R = E + N$



- Anomalies: $SU(2)_L^2 \times U(1)_\zeta \to \mathcal{A}_1^{\rm SM} = -2$

$$SU(2)_R^2 \times U(1)_\zeta \to \mathcal{A}_2^{\rm SM} = +2$$

- $\longrightarrow$ Add $SU(2)_{L/R}$ doublets to cancel gauge anomalies

- M_R scale: $\langle N \rangle$ breaks $SU(2)_R$

- $\rightarrow U(1)_Y = \frac{1}{3}U(1)_C + \frac{1}{2}U(1)_R$ & $U(1)_{Z'} = \frac{1}{5}U(1)_C - \frac{2}{5}U(1)_R + U(1)_\zeta$

- Type III seesaw mechanism $\longrightarrow$ add singlets

- Gauge coupling unification $\longrightarrow$ add triplets

- Scales: $M_{String} > M_R > M_D > M_{Z'} > M_{SUSY} > M_Z$

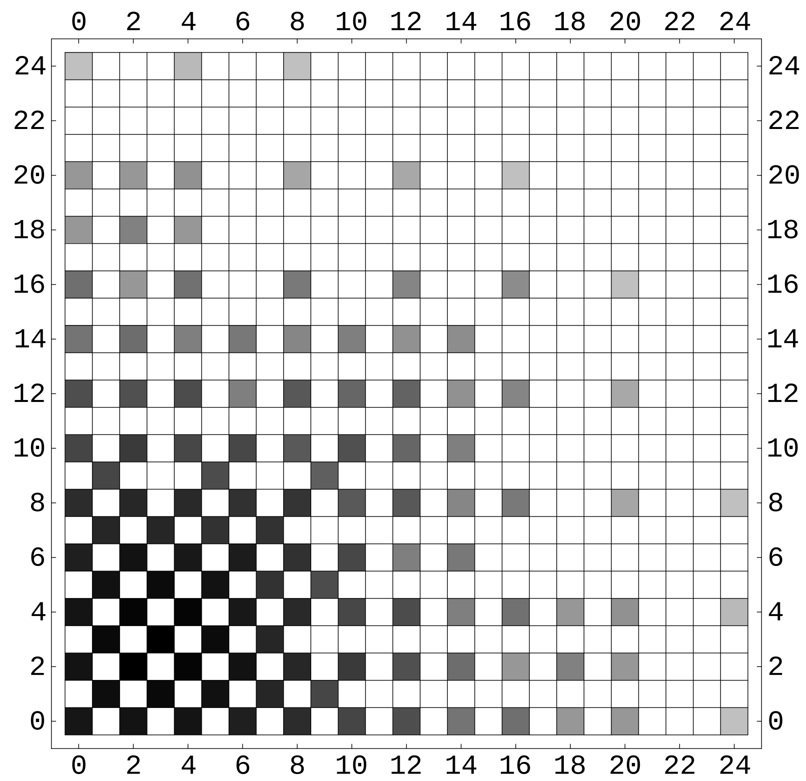
- $\alpha_s(M_Z) \approx 0.1$ & $\sin^2\theta(M_Z) \approx 0.231$

$$M_{SUSY} \approx 1\mathrm{TeV};\ \ M_{Z'} > 10^8\mathrm{GeV};\ \ M_D > 10^{12}\mathrm{GeV};\ \ M_R \approx M_{string}$$

$E_6SSM \rightarrow M_{Z'} \approx 10\mathrm{TeV}$ $\longrightarrow$ Anomaly free $U(1)_\zeta$?

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

$SU(6) \times SU(2)$ models: (with Rizos & Tamvakis)

- $E_8 \rightarrow 248 = 120_A + 128_S \rightarrow E_6 \rightarrow SU(6) \times SU(2)_{L/R} \times U(1)_\zeta$

$$27 = (16_S + 10_V + 1_V) \rightarrow (15,1) + (\bar{6},2)$$

$\Rightarrow$ $U(1)_{Z'}$ with E_6 embedding

- 3 family string model; required Higgs; top Yukawa; exophobic; flat

(Laura Bernard, AEF, Ivan Glasser, John Rizos, Hasan Sonmez, 1208:2145)

- Under $(SU(4) \times SU(2)_R \times U(1)) \otimes SU(2)_L$

$$(15,1) = ([U + D + E + N]_S + [\mathcal{D} + \bar{\mathcal{D}}]_V + \mathcal{S}_V)$$

$$\langle \mathcal{S} \rangle \Rightarrow SU(6) \rightarrow SU(4) \times SU(2)$$

BUT $\langle N \rangle \Rightarrow SU(6) \rightarrow SU(4)' \times SU(2)'$

Need <Adjoint> to keep $U(1)_{Z'}$ unbroken

Conclusions

- DATA $\longrightarrow$ HIGH SCALE UNIFICATION

- STRINGS $\longrightarrow$ GAUGE & GRAVITY UNIFICATION

- STRING CONSISTENCY REQUIRES EXTRA $U(1)$s
- EXPERIMENTAL PREDICTIONS ? Light Z'?

motivated by proton stability; μ–term ...

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