

Light Z' in heterotic string models



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

Constraints

Constructions

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DATA \rightarrow STANDARD MODEL

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

$$\left[\begin{pmatrix} \nu \\ e \end{pmatrix} + D_L^c \right] + \left[U_L^c + \begin{pmatrix} u \\ d \end{pmatrix} + E_L^c \right] + N_L^c$$
$$\bar{5} \quad + \quad 10 \quad + \quad 1 \quad \quad \quad \frac{\quad}{16}$$

STANDARD MODEL \rightarrow 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 $\sim 175\text{--}180\text{GeV}$ 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)

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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)

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Orientifolds

Cvetic, Shiu, Uranga (2001)

Ibanez, Marchesano, Rabadan (2001)

Kiristis, Schellekens, Tsulaia (2008)

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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** $U(1)s \notin SO(10) \rightarrow \tau_P$ & M_{ν_L} PLB 388 (1996) 532
- **Pati's** $U(1)s$ broken at M_{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)

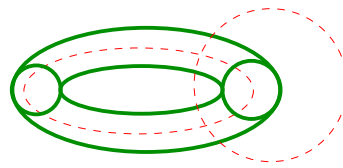
Free Fermionic Construction

Left-Movers: $\psi_{1,2}^\mu$, χ_i , y_i , ω_i ($i = 1, \dots, 6$)

Right-Movers

$$\bar{\phi}_{A=1, \dots, 44} = \left\{ \begin{array}{ll} \bar{y}_i, \bar{\omega}_i & i = 1, \dots, 6 \\ \bar{\eta}_i & i = 1, 2, 3 \\ \bar{\psi}_{1, \dots, 5} \\ \bar{\phi}_{1, \dots, 8} \end{array} \right.$$

$$V \longrightarrow V$$



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

$$Z = \sum_{\text{all spin structures}} c\left(\begin{array}{c} \vec{\alpha} \\ \vec{\beta} \end{array}\right) Z\left(\begin{array}{c} \vec{\alpha} \\ \vec{\beta} \end{array}\right)$$

Models \longleftrightarrow Basis vectors + one-loop phases

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

$$\begin{aligned}
 Z = & \int \frac{d^2\tau}{\tau_2^2} \frac{\tau_2^{-1}}{\eta^{12}\bar{\eta}^{24}} \frac{1}{2^3} \left(\sum (-)^{a+b+ab} \vartheta \begin{bmatrix} a \\ b \end{bmatrix} \vartheta \begin{bmatrix} a+h_1 \\ b+g_1 \end{bmatrix} \vartheta \begin{bmatrix} a+h_2 \\ b+g_2 \end{bmatrix} \vartheta \begin{bmatrix} a+h_3 \\ b+g_3 \end{bmatrix} \right)_{\psi\mu}, \\
 & \times \left(\frac{1}{2} \sum_{\epsilon,\xi} \bar{\vartheta} \begin{bmatrix} \epsilon \\ \xi \end{bmatrix}^5 \bar{\vartheta} \begin{bmatrix} \epsilon+h_1 \\ \xi+g_1 \end{bmatrix} \bar{\vartheta} \begin{bmatrix} \epsilon+h_2 \\ \xi+g_2 \end{bmatrix} \bar{\vartheta} \begin{bmatrix} \epsilon+h_3 \\ \xi+g_3 \end{bmatrix} \right)_{\bar{\psi}^{1\dots 5}, \bar{\eta}^{1,2,3}} \\
 & \times \left(\frac{1}{2} \sum_{H_1, G_1} \frac{1}{2} \sum_{H_2, G_2} (-)^{H_1 G_1 + H_2 G_2} \bar{\vartheta} \begin{bmatrix} \epsilon+H_1 \\ \xi+G_1 \end{bmatrix}^4 \bar{\vartheta} \begin{bmatrix} \epsilon+H_2 \\ \xi+G_2 \end{bmatrix}^4 \right)_{\bar{\phi}^{1\dots 8}} \\
 & \times \left(\sum_{s_i, t_i} \Gamma_{6,6} \begin{bmatrix} h_i | s_i \\ g_i | t_i \end{bmatrix} \right)_{(y\omega\bar{y}\bar{\omega})^{1\dots 6}} \times e^{i\pi\Phi(\gamma, \delta, s_i, t_i, \epsilon, \xi, h_i, g_i, H_1, G_1, H_2, G_2)}
 \end{aligned}$$

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

The NAHE set:

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

$$S = \{\psi^\mu, \chi^{1,\dots,6}\},$$

$N = 4$ Vacua

$$b_1 = \{\chi^{34}, \chi^{56}, y^{34}, y^{56} \mid \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\},$$

$N = 4 \rightarrow N = 2$

$$b_2 = \{\chi^{12}, \chi^{56}, y^{12}, \omega^{56} \mid \bar{y}^{12}, \bar{\omega}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\},$$

$N = 2 \rightarrow N = 1$

$$b_3 = \{\chi^{12}, \chi^{34}, \omega^{12}, \omega^{34} \mid \bar{\omega}^{12}, \bar{\omega}^{34}, \bar{\eta}^3, \bar{\psi}^{1,\dots,5}\},$$

$N = 2 \rightarrow N = 1$

$Z_2 \times Z_2$ orbifold compactification

\implies 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

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

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

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

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 Matter ; 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: $\lambda QQQQL\frac{1}{M} \Rightarrow (\frac{\lambda}{M}) \leq 10^{-26}$

Appealing Proposition:

Low scale gauged $U(1)$ symmetry

Additional Facts

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

Dimension four: $16^4 \Rightarrow \eta'_1 U D D \frac{\langle N \rangle}{M} + \eta'_2 Q L D \frac{\langle N \rangle}{M}$

+ ... dimension five ; dimension six

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

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

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 \rightarrow seven extra $U(1)$'s

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

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 conjunction 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 $SO(10) \rightarrow$ subgroup $b(\bar{\psi}_{\frac{1}{2}}^{1\cdots 5})$:

1. $b\{\bar{\psi}_{\frac{1}{2}}^{1\cdots 5} \bar{\eta}^1 \bar{\eta}^2 \bar{\eta}^3\} = \left\{ \frac{111111}{222222} \frac{111}{222} \right\} \Rightarrow SU(5) \times U(1) \quad U(1) \quad U(1) \quad U(1)$
2. $b\{\bar{\psi}_{\frac{1}{2}}^{1\cdots 5} \bar{\eta}^1 \bar{\eta}^2 \bar{\eta}^3\} = \{ 11100 \quad 000 \} \Rightarrow SO(6) \times SO(4) \quad U(1) \quad U(1) \quad U(1)$

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

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

2. $b\{\bar{\psi}_{\frac{1}{2}}^{1\cdots 5} \bar{\eta}^1 \bar{\eta}^2 \bar{\eta}^3\} = \{ 11100 \quad 000 \} \Rightarrow SO(6) \times SO(4) \quad U(1) \quad U(1) \quad U(1)$
3. $b\{\bar{\psi}_{\frac{1}{2}}^{1\cdots 5} \bar{\eta}^1 \bar{\eta}^2 \bar{\eta}^3\} = \left\{ \frac{111}{222} 00 \frac{111}{222} \right\} \Rightarrow$
 $SU(3)_C \times U(1)_C \times SU(2)_L \times SU(2)_R \quad U(1) \quad U(1) \quad U(1)$

$U(1)$ matter charges

in cases 1. 2.

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

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

In the LRS model of case 3.

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

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

\implies 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 :

$$Q_L Q_L Q_L L_L \rightarrow QQQ L$$

$$Q_R Q_R Q_R L_R \rightarrow \{UDDN, UUDE\}$$

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:

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

are allowed

STRING DERIVED LEFT-RIGHT SYMMETRIC MODEL

	ψ^μ	χ^{12}	χ^{34}	χ^{56}	$y^{3,\dots,6}$	$\bar{y}^{3,\dots,6}$	$y^{1,2}, \omega^{5,6}$	$\bar{y}^{1,2}, \bar{\omega}^{5,6}$	$\omega^{1,\dots,4}$	$\bar{\omega}^{1,\dots,4}$	$\bar{\psi}^{1,\dots,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^{1,\dots,8}$
1	1	1	1	1	1, ..., 1	1, ..., 1	1, ..., 1	1, ..., 1	1, ..., 1	1, ..., 1	1, ..., 1	1	1	1	1, ..., 1
<i>S</i>	1	1	1	1	0, ..., 0	0, ..., 0	0, ..., 0	0, ..., 0	0, ..., 0	0, ..., 0	0, ..., 0	0	0	0	0, ..., 0
<i>b</i> ₁	1	1	0	0	1, ..., 1	1, ..., 1	0, ..., 0	0, ..., 0	0, ..., 0	0, ..., 0	1, ..., 1	1	0	0	0, ..., 0
<i>b</i> ₂	1	0	1	0	0, ..., 0	0, ..., 0	1, ..., 1	1, ..., 1	0, ..., 0	0, ..., 0	1, ..., 1	0	1	0	0, ..., 0
<i>b</i> 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}	$y^3 y^6$	$y^4 \bar{y}^4$	$y^5 \bar{y}^5$	$\bar{y}^3 \bar{y}^6$	$y^1 \omega^5$	$y^2 \bar{y}^2$	$\omega^6 \bar{\omega}^6$	$\bar{y}^1 \bar{\omega}^5$	$\omega^2 \omega^4$	$\omega^1 \bar{\omega}^1$	$\omega^3 \bar{\omega}^3$	$\bar{\omega}^2 \bar{\omega}^4$	$\bar{\psi}^{1,\dots,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^{1,\dots,8}$
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 0
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 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

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Leptophobic Z'

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

In the LRS models

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

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

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

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

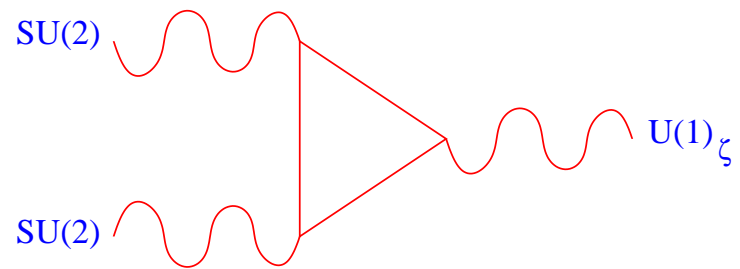
$$Q_{B'}(Q_R) = -\frac{1}{2} - \frac{1}{2} = -1$$

→

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

• 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: $SU(2)_L^2 \times U(1)_\zeta \rightarrow \mathcal{A}_1^{\text{SM}} = -2$

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

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

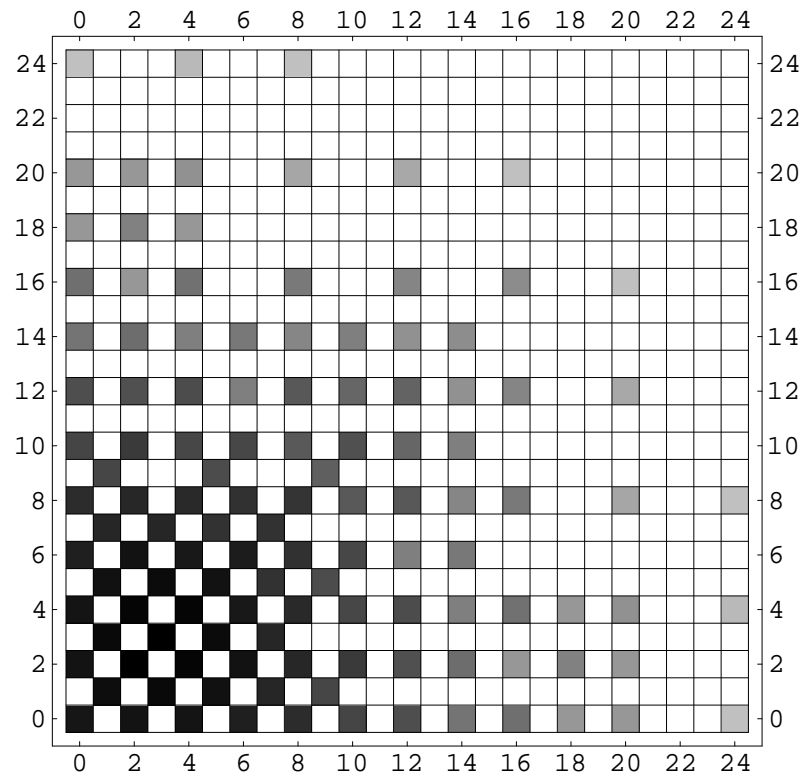
- M_R scale: $\langle N \rangle$ breaks $SU(2)_R$
- $\rightarrow U(1)_Y = \frac{1}{3}U(1)_C + \frac{1}{2}U(1)_R$ & $U(1)_{Z'} = \frac{1}{5}U(1)_C - \frac{2}{5}U(1)_R + U(1)_\zeta$
- Type III seesaw mechanism \rightarrow add singlets
- Gauge coupling unification \rightarrow add triplets
- Scales: $M_{String} > M_R > M_D > M_{Z'} > M_{SUSY} > M_Z$
- $\alpha_s(M_Z) \approx 0.1$ & $\sin^2 \theta(M_Z) \approx 0.231$

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

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

Spinor–vector duality:

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



Symmetric under exchange of rows and columns

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

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 $\langle \text{Adjoint} \rangle$ 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 $M_{Z'} \sim \text{TeV}$ in heterotic string constructions ...