

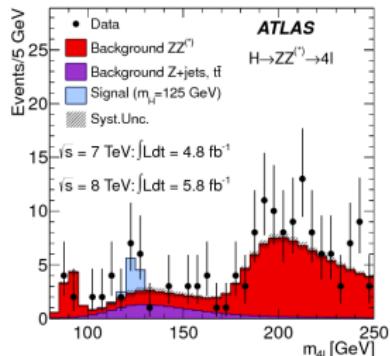
BSM Physics from Enlarged Gauge Symmetry: the 331 Model - a case of study

Antonio Costantini

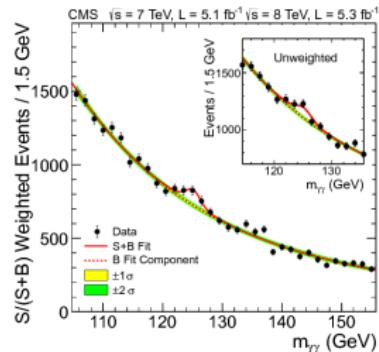
EPS-HEP 2019

11st July 2019

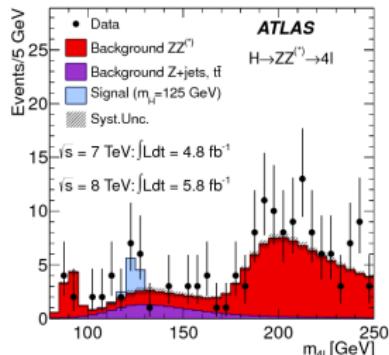




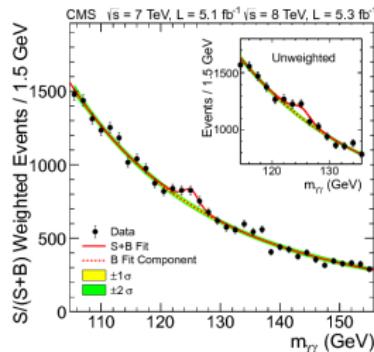
ATLAS Collaboration, Phys.Lett. B716 (2012) 1-29



CMS Collaboration, Phys.Lett. B716 (2012) 30-61



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CMS Collaboration, Phys.Lett. B716 (2012) 30-61

- ◊ dark matter
- ◊ neutrino mass
- ◊ $\Lambda_{EW} \ll M_{Planck}$
- ◊ $n_{Q_f} = n_{L_f} = 3$
- ◊ ...

Content

331 Model

$$\beta^{\text{em}} = \sqrt{3}$$

Same-Sign Leptons Phenomenology

Toward GUT

Field Content

$$\mathcal{G} \equiv SU(3)_c \times \mathbf{SU(3_L)} \times U(1)_X$$

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$$Q_1 = \begin{pmatrix} u \\ d \\ D \end{pmatrix}, \quad Q_2 = \begin{pmatrix} c \\ s \\ S \end{pmatrix}, \quad Q_{1,2} \in (3, 3, X_{Q_{1,2}})$$

$$Q_3 = \begin{pmatrix} b \\ t \\ T \end{pmatrix}, \quad Q_3 \in (3, \bar{3}, X_{Q_3})$$

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$$\chi = \begin{pmatrix} \chi^A \\ \chi^B \\ \chi^0 \end{pmatrix} \in (1, 3, X_\chi), \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{-B} \end{pmatrix} \in (1, 3, X_\rho), \quad \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^{-A} \end{pmatrix} \in (1, 3, X_\eta)$$

\mathcal{Q}^{em} in the 331 Model

$SU(3)$ has two diagonal generators



$$\mathcal{Q}_3^{\text{em}} = Y_3 + T_3 \quad \mathcal{Q}_{\bar{3}}^{\text{em}} = Y_{\bar{3}} - T_3$$

\mathcal{Q}^{em} in the 331 Model

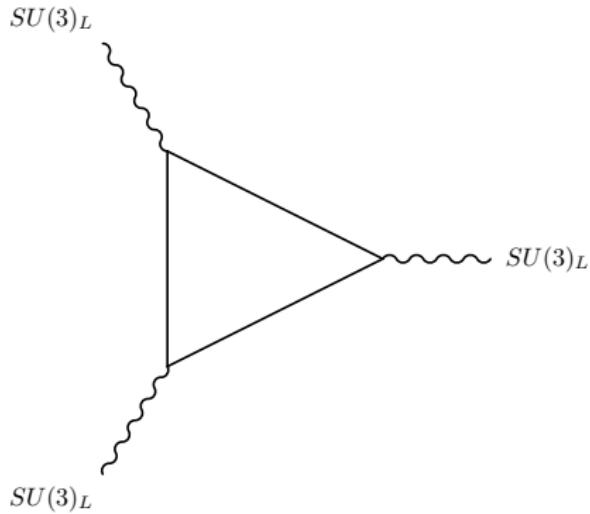
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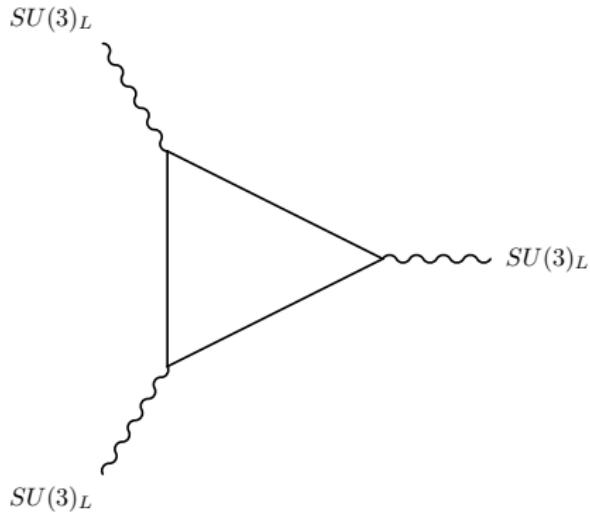
$$\mathcal{Q}_{\mathbf{3}}^{\text{em}} = Y_{\mathbf{3}} + T_3 \quad \mathcal{Q}_{\bar{\mathbf{3}}}^{\text{em}} = Y_{\bar{\mathbf{3}}} - T_3$$

$$Y_{\mathbf{3}} = \beta^{\text{em}} T_8 + X\mathbf{1} \quad Y_{\bar{\mathbf{3}}} = -\beta^{\text{em}} T_8 + X\mathbf{1}$$

Anomaly Cancellation: the $SU(3)_L$ example



Anomaly Cancellation: the $SU(3)_L$ example



$$Q_1 = +3 \times 3_c$$

$$Q_2 = +3 \times 3_c$$

$$Q_3 = -3 \times 3_c$$

$$L = -3 \times 3_f$$

$$n_{Q_f} = n_{L_f} = 3 \kappa$$

β^{em} Parameter: Possible Values in the 331

The β parameter is constrained from the Z' mass expression. Has to satisfy

$$1 - (1 + (\beta^{\text{em}})^2) s_W^2 > 0$$



$$|\beta^{\text{em}}| < \sqrt{3}$$

β^{em} Parameter: Possible Values in the 331

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$\beta^{\text{em}} = \frac{n}{\sqrt{3}}$, $n = 1, 2, 3$ gives fractional electric charge for various particle. $n = 2$ imply $\pm 5/6$ and $\pm 7/6$ for the electric charge of heavy fermions and $\pm 1/2$ and $\pm 3/2$ for heavy leptons.

Buras, De Fazio, Girrbach, JHEP 1402 (2014) 112

$\beta^{\text{em}} = 0$ gives leptons/bosons with charge $\pm 1/2$ and quarks with charge $\pm 1/6$

Hue, Ninh, Mod.Phys.Lett. A31 (2016) no.10, 1650062

Field Content for Generic β^{em}

particles	$Q(\beta^{\text{em}})$	$\beta^{\text{em}} = -\frac{1}{\sqrt{3}}$	$\beta^{\text{em}} = \frac{1}{\sqrt{3}}$	$\beta^{\text{em}} = -\sqrt{3}$	$\beta^{\text{em}} = \sqrt{3}$
D, S	$\frac{1}{6} - \frac{\sqrt{3}\beta^{\text{em}}}{2}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{5}{3}$	$-\frac{4}{3}$
T	$\frac{1}{6} + \frac{\sqrt{3}\beta^{\text{em}}}{2}$	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{4}{3}$	$\frac{5}{3}$
E	$-\frac{1}{2} + \frac{\sqrt{3}\beta^{\text{em}}}{2}$	-1	0	-2	1
V	$-\frac{1}{2} + \frac{\sqrt{3}\beta^{\text{em}}}{2}$	-1	0	-2	1
Y	$\frac{1}{2} + \frac{\sqrt{3}\beta^{\text{em}}}{2}$	0	1	-1	2
H_V	$-\frac{1}{2} + \frac{\sqrt{3}\beta^{\text{em}}}{2}$	-1	0	-2	1
H_Y	$\frac{1}{2} + \frac{\sqrt{3}\beta^{\text{em}}}{2}$	0	1	-1	2
H_W	1	1	1	1	1

Cao, Liu, Xie, Yan, Zhang, Phys.Rev. D93 (2016) no.7, 075030

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$$Q_3 = \begin{pmatrix} b_L \\ t_L \\ T_L \end{pmatrix}, \quad Q_3 \in (3, \bar{3}, 2/3)$$

$$I = \begin{pmatrix} I_L \\ \nu_I \\ J_R^c \end{pmatrix}, \quad I \in (1, \bar{3}, 0), \quad I = e, \mu, \tau$$

$$\chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix} \in (1, 3, 1), \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix} \in (1, 3, 0), \quad \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^{--} \end{pmatrix} \in (1, 3, -1)$$

From $SU(3)_L \times U(1)_X$ to $U(1)_{\text{em}}$

$$SU(3)_L \times U(1)_X$$

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$$\begin{array}{c} \| \\ \langle \chi \rangle \\ \Downarrow \end{array}$$

$SU(2)_L \times U(1)_Y$

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$$U(1)_{\text{em}}$$

From $SU(3)_L \times U(1)_X$ to $U(1)_{\text{em}}$

$$SU(3)_L \times U(1)_X \quad W_1, \dots, W_8, B_X$$

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$$SU(2)_L \times U(1)_Y \quad W_1, W_2, W_3, B_Y, V^\pm, Y^{\pm\pm}, Z'$$

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$$U(1)_{\text{em}} \quad \gamma, Z, Z', W^\pm, V^\pm, Y^{\pm\pm}$$

Yukawa Interactions: Quark Sector

$$\begin{aligned}\mathcal{L}_{q,triplet}^{Yuk.} = & (y_d^1 Q_1 \rho^* d_R + y_d^2 Q_2 \rho^* s_R + y_d^3 Q_3 \eta b_R^* \\ & + y_u^1 Q_1 \eta^* u_R^* + y_u^2 Q_2 \eta^* c_R^* + y_u^3 Q_3 \rho t_R^* \\ & + y_E^1 Q_1 \chi^* D_R^* + y_E^2 Q_2 \chi^* S_R^* + y_E^3 Q_3 \chi T_R^*) + \text{h.c.}\end{aligned}$$

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$$v_\chi \gg v_{\eta, \rho}$$



$$m_{D,S,T} = \mathcal{O}(TeV) \text{ if } y_E^i \sim 1$$

Yukawa Interactions: Lepton Sector

$$\begin{aligned}\mathcal{L}_{l, \text{triplet}}^{\text{Yuk}} &= G_{ab}^\rho (l_{a\alpha}^i \epsilon^{\alpha\beta} l_{b\beta}^j) \rho^{*k} \epsilon^{ijk} + \text{h.c.} \\ &= G_{ab}^\rho (l_a^i \cdot l_b^j) \rho^{*k} \epsilon^{ijk} + \text{h.c.}\end{aligned}$$

a and b are flavour indices

α and β are Weyl indices ($l_a^i \cdot l_b^j \equiv l_{a\alpha}^i \epsilon^{\alpha\beta} l_{b\beta}^j$)

$i, j, k = 1, 2, 3$, are $SU(3)_L$ indices

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$i, j, k = 1, 2, 3$, are $SU(3)_L$ indices

$l_a^i \cdot l_b^j \rho^{*k} \epsilon^{ijk}$ is antisymmetric
↓

G_{ab}^ρ has to be antisymmetric

Yukawa Interactions: Lepton Sector

$$\mathcal{L}_{I,\text{sextet}}^{\text{Yuk.}} = G_{ab}^\sigma l_a^i \cdot l_b^j \sigma_{i,j}^*$$

with

$$\sigma = \begin{pmatrix} \sigma_1^{++} & \sigma_1^+/\sqrt{2} & \sigma_1^0/\sqrt{2} \\ \sigma_1^+/\sqrt{2} & \sigma_1^0 & \sigma_2^-/\sqrt{2} \\ \sigma_1^0/\sqrt{2} & \sigma_2^-/\sqrt{2} & \sigma_2^{--} \end{pmatrix} \in (1, 6, 0)$$

G_{ab}^σ is symmetric

Yukawa Interactions: Lepton Sector

$$\mathcal{L}_{I,\text{sextet}}^{\text{Yuk.}} = G_{ab}^\sigma I_a^i \cdot I_b^j \sigma_{i,j}^*$$

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G_{ab}^σ is symmetric

$H^{\pm\pm} \rightarrow I^\pm I^\pm$ allowed ($\rho \not> \rho^{\pm\pm}$)

Content

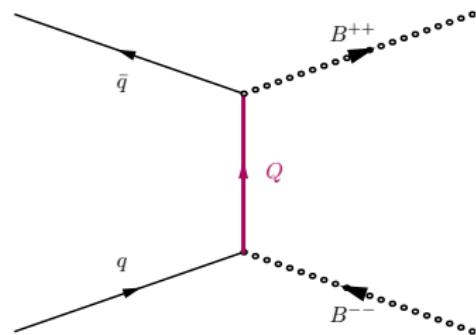
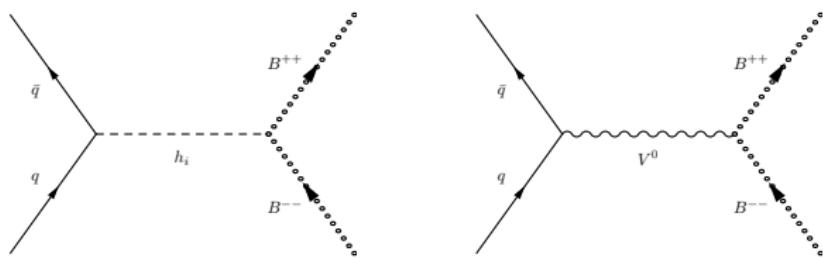
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Same-Sign Leptons Phenomenology

Toward GUT

$B^{\pm\pm}$ @ the LHC



arXiv:1806.04536 [hep-ph]

Signal & Backgrounds at 13 TeV

Benchmark Point

$$m_{Y^{\pm\pm}} \simeq m_{H^{\pm\pm}} \sim 870 \text{ GeV}$$

$$Br(Y^{\pm\pm} \rightarrow l^\pm l^\pm) = Br(H^{\pm\pm} \rightarrow l^\pm l^\pm) = \frac{1}{3}$$

SIGNAL

$$pp \rightarrow Y^{++} Y^{--} (H^{++} H^{--}) \rightarrow (l^+ l^+) (l^- l^-) \quad l = e, \mu$$

$$\sigma(pp \rightarrow YY \rightarrow 4l) \simeq 4.3 \text{ fb} \quad \sigma(pp \rightarrow HH \rightarrow 4l) \simeq 0.3 \text{ fb}$$

BACKGROUNDS

$$pp \rightarrow ZZ \rightarrow (l^+ l^-) (l^+ l^-)$$

$$\sigma(pp \rightarrow ZZ \rightarrow 4l) \simeq 6.1 \text{ fb}$$

Number of Events (13 TeV and $\mathcal{L}=300 \text{ fb}^{-1}$)

Defining the significance s to discriminate a signal S from a background B as

$$\sigma_S = \frac{S}{\sqrt{B + \sigma_B^2}},$$

σ_B systematic error on B ($\sigma_B \simeq 0.1B$)

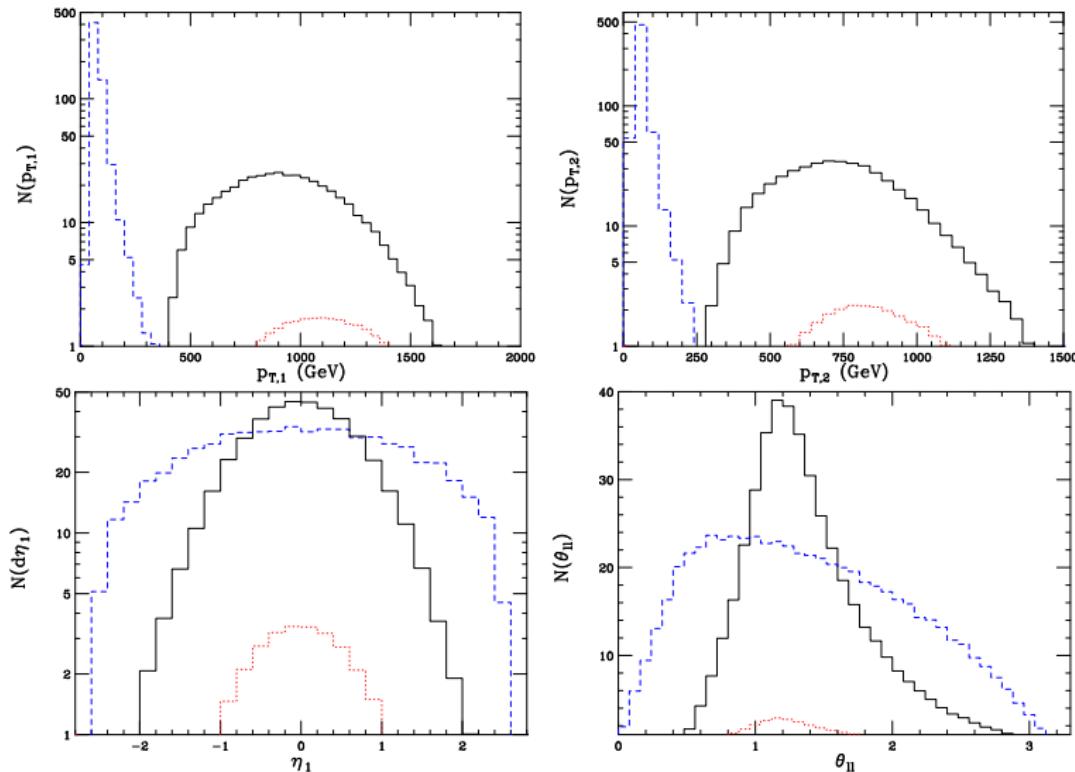
$$N(YY) \simeq 1302, \ N(HH) \simeq 120, \ N(ZZ) \simeq 1836$$



$$\sigma_{YY} \simeq 6.9, \ \sigma_{HH}^{B_{SM}} = 0.6, \ \sigma_{HH}^{B_{YY}} = 0.9$$

arXiv:1806.04536 [hep-ph]

Distributions



Background, Scalar, Vector

arXiv:1806.04536 [hep-ph]

Content

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Toward GUT

Trinification

$$[SU(3)]^3 \equiv SU(3)_c \times SU(3)_L \times SU(3)_R$$

....maximal subgroup of E_6

Trinification: Field Content

$$H = \begin{pmatrix} h_{11}^0 & h_{12}^+ & h_{13}^+ \\ h_{21}^- & h_{22}^0 & h_{23}^0 \\ h_{31}^- & h_{32}^0 & h_{33}^0 \end{pmatrix} \in (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{3})$$

$$L = \begin{pmatrix} L_1^1 & E^- & e^- \\ E^+ & L_2^2 & \nu \\ e^+ & \hat{\nu} & L_3^3 \end{pmatrix} \in (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{3})$$

$$Q_L = \begin{pmatrix} u_L \\ d_L \\ D_L \end{pmatrix} \in (\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1})$$

$$Q_R = \begin{pmatrix} \bar{u}_R & \bar{d}_R & \bar{D}_R \end{pmatrix} \in (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}})$$

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$$\mathcal{Q}^{\text{em}} = \mathcal{T}_L^3 + \mathcal{T}_R^3 + \frac{1}{\sqrt{3}} \mathcal{T}_L^8 + \frac{1}{\sqrt{3}} \mathcal{T}_R^8$$

Trinification: Field Content

$$H = \begin{pmatrix} h_{11}^0 & h_{12}^+ & h_{13}^+ \\ h_{21}^- & h_{22}^0 & h_{23}^0 \\ h_{31}^- & h_{32}^0 & h_{33}^0 \end{pmatrix} \in (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{3})$$

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$$\mathcal{Q}_{D_i}^{\text{em}} = -1/3$$

non-Exotic Quarks!

$$SU(3)^3 \rightarrow \dots \rightarrow \mathcal{G}_{SM} \rightarrow SU(3)_c \times U(1)_{\text{em}}$$

$$\langle H_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 & 0 & 0 \\ 0 & b_1 & 0 \\ 0 & 0 & M_1 \end{pmatrix}, \quad \langle H_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 & 0 & 0 \\ 0 & b_2 & b_3 \\ 0 & M & M_2 \end{pmatrix}$$

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$$SU(3)^3 \xrightarrow{M_i} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$SU(3)^3 \rightarrow \dots \rightarrow \mathcal{G}_{SM} \rightarrow SU(3)_c \times U(1)_{\text{em}}$$

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$$\begin{aligned} SU(3)^3 &\xrightarrow{M_i} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ &\xrightarrow{M} \mathcal{G}_{SM} \\ &\xrightarrow{v_i, b_j} SU(3)_c \times U(1)_{\text{em}} \end{aligned}$$

$$(\sqrt{2} G_F)^{1/2} \sim v_i, \quad b_j < M < M_i \sim m_{GUT}$$

Hetzel, Stech, Phys.Rev.D91 (2015) 055026

Not-Exotic...but Heavy!

$$m_{D_i} = \frac{1}{\sqrt{2}} M_{1,2} Y_{Q_i} \lesssim m_{GUT}$$



$\mathcal{G}_{331} \subset [SU(3)]^3$: Spontaneous Symmetry Breaking Chain

$$SU(3) \rightarrow SU(2)_a \times U(1)_b$$



$$3 \rightarrow 2_b + 1_{-2b}$$

$\mathcal{G}_{331} \subset [SU(3)]^3$: Spontaneous Symmetry Breaking Chain

$$SU(3) \rightarrow SU(2)_a \times U(1)_b$$



$$3 \rightarrow 2_b + 1_{-2b}$$

$$SU(2)_a \rightarrow U(1)_a$$



$$2_b + 1_{-2b} \rightarrow 1_{a,b} + 1_{-a,b} + 1_{0,-2b}$$

$\mathcal{G}_{331} \subset [SU(3)]^3$: Spontaneous Symmetry Breaking Chain

$$SU(3) \rightarrow SU(2)_a \times U(1)_b$$



$$3 \rightarrow 2_b + 1_{-2b}$$

$$SU(2)_a \rightarrow U(1)_a$$



$$2_b + 1_{-2b} \rightarrow 1_{a,b} + 1_{-a,b} + 1_{0,-2b}$$

Thus, when $SU(3)_R$ breaks into $U(1)_a \otimes U(1)_b$ the following branching rule applies:

$$3_R \rightarrow (a)(b) + (-a)(b) + (0)(-2b)$$

Conclusions

- ◊ SM issues: dark matter, neutrino masses ... → needs to be improved
- ◊ models with larger gauge symmetry have rich phenomenology
- ◊ 331 model(s) explain the observed number of fermion families ($n_{Q_f} = n_{L_f} = 3\kappa$)
- ◊ minimal version of 331 has the almost unique feature of doubly-charged gauge boson
- ◊ models with larger gauge group appear in GUT theories

LUCA
SCHOOL
OF
ARTS

**WE ARE A
NOT FOR
NO**

BACKUP

The Scalars for Generic β^{em}

The scalars of the 331 model, responsible for the electroweak symmetry breaking, come in 3 triplets of $SU(3)_L$ (plus an additional sextet).

$$\chi = \begin{pmatrix} \chi^A \\ \chi^B \\ \chi^0 \end{pmatrix} \in (1, 3, 1), \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^B \end{pmatrix} \in (1, 3, 0), \quad \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^A \end{pmatrix} \in (1, 3, -1)$$

Beside neutral and singly-charged states, we have states with charge

$$Q^A = \frac{1}{2} + \frac{\sqrt{3}}{2} \beta^{\text{em}}, \quad Q^B = -\frac{1}{2} + \frac{\sqrt{3}}{2} \beta^{\text{em}}$$

The Scalar Potential: the Triplet Sector

The potential is then given by the expression

$$\begin{aligned}V = & m_1 \rho^* \rho + m_2 \eta^* \eta + m_3 \chi^* \chi \\& + \lambda_1 (\rho^* \rho)^2 + \lambda_2 (\eta^* \eta)^2 + \lambda_3 (\chi^* \chi)^2 \\& + \lambda_{12} \rho^* \rho \eta^* \eta + \lambda_{13} \rho^* \rho \chi^* \chi + \lambda_{23} \eta^* \eta \chi^* \chi \\& + \zeta_{12} \rho^* \eta \eta^* \rho + \zeta_{13} \rho^* \chi \chi^* \rho + \zeta_{23} \eta^* \chi \chi^* \eta \\& + \sqrt{2} f_{\rho \eta \chi} \rho \eta \chi\end{aligned}$$

Minimization Conditions

The neutral component of each triplet gets vev and is expanded as

$$\rho^0 = \frac{1}{\sqrt{2}}v_\rho + \frac{1}{\sqrt{2}}(\text{Re } \rho^0 + i \text{Im } \rho^0)$$

$$\eta^0 = \frac{1}{\sqrt{2}}v_\eta + \frac{1}{\sqrt{2}}(\text{Re } \eta^0 + i \text{Im } \eta^0)$$

$$\chi^0 = \frac{1}{\sqrt{2}}v_\chi + \frac{1}{\sqrt{2}}(\text{Re } \chi^0 + i \text{Im } \chi^0)$$

The minimization conditions of the potential, defined by $\frac{\partial V}{\partial \Phi}|_{\Phi=0} = 0$, are given by

$$m_1 v_\rho + \lambda_1 v_\rho^3 + \frac{\lambda_{12}}{2} v_\rho v_\eta^2 - f_{\rho\eta\chi} v_\eta v_\chi + \frac{\lambda_{13}}{2} v_\rho v_\chi^2 = 0$$

$$m_2 v_\eta + \lambda_2 v_\eta^3 + \frac{\lambda_{12}}{2} v_\rho^2 v_\eta - f_{\rho\eta\chi} v_\rho v_\chi + \frac{\lambda_{23}}{2} v_\eta v_\chi^2 = 0$$

$$m_3 v_\chi + \lambda_3 v_\chi^3 + \frac{\lambda_{13}}{2} v_\rho^2 v_\chi - f_{\rho\eta\chi} v_\rho v_\eta + \frac{\lambda_{23}}{2} v_\eta^2 v_\chi = 0$$

Scalars

The CP-even neutral scalars mix as

$$h_i = \mathcal{R}_{ij}^S H_j$$

where $\vec{H} = (\text{Re } \rho^0, \text{Re } \eta^0, \text{Re } \chi^0)$ and $\vec{h} = (h_1, h_2, h_3)$. Moreover we have introduced the dimensionless parameter κ defined by $f_{\rho\eta\chi} = \kappa v_\chi$ in order to have a single scale v_χ and $\beta = \tan^{-1} v_\eta / v_\rho$, $v = \sqrt{v_\eta^2 + v_\rho^2}$.

The explicit expression of the mass matrices of the neutral scalars is given by

$$m_h^2 = \begin{pmatrix} \kappa \tan \beta v_\chi^2 + 2\lambda_1 v^2 \cos^2 \beta & \lambda_{12} v^2 \cos \beta \sin \beta - \kappa v_\chi^2 & v_\chi v(\lambda_{13} \cos \beta - \kappa \sin \beta) \\ \lambda_{12} v^2 \cos \beta \sin \beta - \kappa v_\chi^2 & \kappa \cot \beta v_\chi^2 + 2\lambda_2 v^2 \sin^2 \beta & v_\chi v(\lambda_{23} \sin \beta - \kappa \cos \beta) \\ v_\chi v(\lambda_{13} \cos \beta - \kappa \sin \beta) & v_\chi v(\lambda_{23} \sin \beta - \kappa \cos \beta) & 2\lambda_3 v_\chi^2 + \kappa v^2 \cos \beta \sin \beta \end{pmatrix}$$

Pseudocalar

After EWSB the CP-odd neutral scalars are defined as

$$a_i = \mathcal{R}_{ij}^P A_j$$

where $\vec{A} = (\text{Im } \rho^0, \text{Im } \eta^0, \text{Im } \chi^0)$ and $\vec{a} = (a_{G_Z}, a_{G_{Z'}}, a_1)$.
The mass matrix for the neutral pseudoscalars is

$$m_a^2 = \begin{pmatrix} \kappa v_\chi^2 \tan \beta & \kappa v_\chi^2 & \kappa v_\chi v \sin \beta \\ \kappa v_\chi^2 & \kappa v_\chi^2 \cot \beta & \kappa v_\chi v \cos \beta \\ \kappa v_\chi v \sin \beta & \kappa v_\chi v \cos \beta & \kappa v^2 \cos \beta \sin \beta \end{pmatrix}$$

and

$$m_{a_1}^2 = \kappa(v_\chi^2 \csc \beta \sec \beta + v^2 \cos \beta \sin \beta)$$

Singly-Charged State

For the singly-charged states we define

$$h_i^- = \mathcal{R}_{ij}^C H_j^-$$

where $\vec{H}^- = ((\rho^+)^*, \eta^-)$ and $\vec{h}^- = (h_{G_W}^-, h_1^-)$. With this definition we have

$$m_{h^\pm}^2 = \begin{pmatrix} \kappa \tan \beta v_\chi^2 + \frac{1}{2} \zeta_{12} v^2 \sin^2 \beta & \kappa v_\chi^2 + \frac{1}{2} \zeta_{12} v^2 \cos \beta \sin \beta \\ \kappa v_\chi^2 + \frac{1}{2} \zeta_{12} v^2 \cos \beta \sin \beta & \kappa \cot \beta v_\chi^2 + \frac{1}{2} \zeta_{12} v^2 \cos^2 \beta \end{pmatrix}$$

and the mass of the singly-charged Higgs boson is

$$m_{h_1^\pm}^2 = \frac{1}{2} \zeta_{12} v^2 + \kappa v_\chi^2 \csc \beta \sec \beta$$

A-Charged State

We now consider the A -charged sector. We define

$$h_i^A = \mathcal{R}_{ij}^A H_j^A$$

where $\vec{H}^A = ((\eta^{-A})^*, \chi^A)$ and $\vec{h}^A = (h_{G_V^A}^A, h_1^A)$. We have

$$m_{h^{\pm A}}^2 = \begin{pmatrix} \frac{1}{2} v_\chi^2 (\zeta_{23} + 2\kappa \cot \beta) & \frac{1}{2} v_\chi v (2\kappa \cos \beta + \zeta_{23} \sin \beta) \\ \frac{1}{2} v_\chi v (2\kappa \cos \beta + \zeta_{23} \sin \beta) & \frac{1}{2} v^2 \sin \beta (2\kappa \cos \beta + \zeta_{23} \sin \beta) \end{pmatrix}$$

and

$$m_{h_1^{\pm A}}^2 = \frac{1}{4} (\zeta_{23} + 2\kappa \cot \beta) (2v_\chi^2 + v^2 - v^2 \cos 2\beta)$$

B-Charged State

For the B-charged sector we have

$$h_i^B = \mathcal{R}_{ij}^B H_j^B$$

where $\vec{H}^B = ((\rho^{-B})^*, \chi^B)$ and $\vec{h}^B = (h_{G_{V^B}}^B, h_1^B)$. The mass matrix is

$$m_{h^{\pm B}}^2 = \begin{pmatrix} \frac{1}{2} v_\chi^2 (\zeta_{13} + 2\kappa \tan \beta) & \frac{1}{2} v_\chi v (2\kappa \sin \beta + \zeta_{13} \cos \beta) \\ \frac{1}{2} v_\chi v (2\kappa \sin \beta + \zeta_{13} \cos \beta) & \frac{1}{2} v^2 \cos \beta (2\kappa \sin \beta + \zeta_{13} \cos \beta) \end{pmatrix}$$

and

$$m_{h_1^{\pm B}}^2 = \frac{1}{4} (\zeta_{13} + 2\kappa \tan \beta) (2v_\chi^2 + v^2 - v^2 \cos 2\beta)$$