SU(3)-Flavons and Pati-Salam-GUTs

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Outline

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1. Running couplings in PS
   - Multi-step breaking of Pati-Salam
   - Gauge coupling Unification
   - Unification Plots
2. Flavour Models
   - Aim of Flavour Models
   - Model of triplet Flavons
   - Model with decuplet flavons
3. Conclusions

Multi-step breaking of SUSY-Pati Salam

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symmetry		valid to
Pati-Salam:	$SU(4) \times SU(2)_R \times SU(2)_L \times Z_2$	M_{Planck}
	$\downarrow \langle \Sigma \rangle$	10^{16}
Left-Right:	$SU(3)_C \times U(1)_{B-L} \times SU(2)_R \times SU(2)_L \times Z_2$	
	$\downarrow \langle H^R \rangle$	10^{13}
Standard model:	$SU(3)_C \times SU(2)_L \times U(1)_Y$	
	$\downarrow \langle h \rangle$	M_Z
	$SU(3)_C \times U(1)_{em}$	

Pati-Salam Higgs content

PS breaking Higgs

$\Sigma = (\mathbf{15}, \mathbf{1}, \mathbf{1})$ to break $SU(4)$
$E = (\mathbf{6}, \mathbf{2}, \mathbf{2})$ and $T_L = (\mathbf{1}, \mathbf{3}, \mathbf{1}), T_R = (\mathbf{1}, \mathbf{1}, \mathbf{3})$

} **45**

L-R breaking Higgs

$H_u^R = (\mathbf{4}, \mathbf{1}, \mathbf{2})$ and $H_d^R = (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2})$ to break $U(1)_{B-L} \times SU(2)_R$
$H_u^L = (\mathbf{4}, \mathbf{2}, \mathbf{1})$ and $H_d^L = (\overline{\mathbf{4}}, \mathbf{2}, \mathbf{1})$ because of Z_2

} $\mathbf{16} \oplus \overline{\mathbf{16}}$

optional MSSM Higgs

$h = (\mathbf{1}, \mathbf{2}, \mathbf{2})$: MSSM-Higgs
$F = (\mathbf{6}, \mathbf{1}, \mathbf{1})$: possibly light triplets

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- full E_6 multiplets $\mathbf{78} \oplus \mathbf{27}^3$ when including matter

Higgs Superpotential

- construct renormalizable Higgs sector superpotential
- calculate tree-level Higgs masses

Results

- see-saw-like mass terms in Higgs fields

  $\Rightarrow$ new intermediate mass-scale: $M_F \sim m_F + \frac{\langle H_R \rangle^2}{\langle \Sigma \rangle}$

  $\rightsquigarrow$ light colour triplets (down to TeV-scale)

  $\rightarrow$ useful for unification

  W. Kilian, J.Reuter: arXiv:hep-ph/0606277

- additionally Z_2-symmetry above L-R-scale

  $\Rightarrow$ two light doublets from H_L (at MSSM-scale)

  $\rightsquigarrow$ makes h optional

  $\rightsquigarrow$ $SU(2)_R$ and $SU(2)_L$ breaking form same $SO(10)$ representation

Requirements for Unification

(1) PS hypercharge condition $Y = T_3^R + \frac{B-L}{2}$

$\rightsquigarrow$ rescaling of $U(1)_Y$

$\rightsquigarrow$ unification-condition at the L-R-scale

$$\alpha_Y^{-1} = \alpha_R^{-1} + \tfrac{2}{3}\alpha_{B-L}^{-1} \quad ; \quad \alpha_R^{-1} = \alpha_L^{-1}$$

(2) unification condition at the PS-scale

$$\alpha_{B-L}^{-1} = \alpha_3^{-1} \quad ; \quad \alpha_3^{-1} = \alpha_4^{-1}$$

(3) complete unification of couplings near the Planck-scale

Inputs:

- MSSM-scale: 250 GeV
- 3 unification-requirements
- but 3 (4) mass-scales + normalization of $U(1)_{B-L}$

$\Rightarrow$ scales are constrained but not fixed

Minimal model

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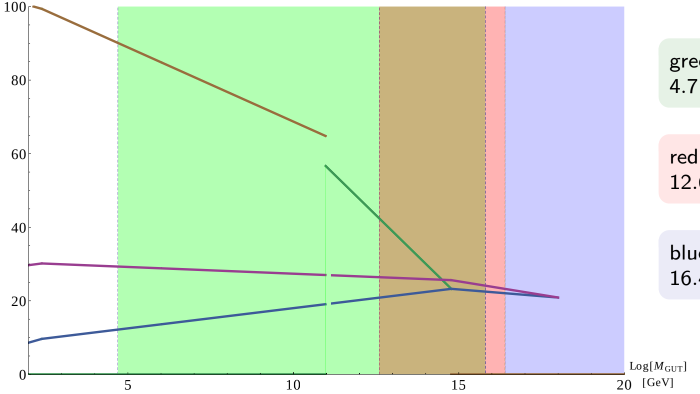
Higgs field content

$$H^R_{u/d} = (\mathbf{4},\mathbf{1},\mathbf{2}) \quad ; \; H^L_{u/d} = (\mathbf{4},\mathbf{2},\mathbf{1}) \quad ; \; \Sigma = (\mathbf{15},\mathbf{1},\mathbf{1})$$



green band:
$4.7 \leq \log\,[M_{L\text{-}R}] \leq 15.8$

red band:
$12.6 \leq \log\,[M_{PS}] \leq 16.4$

blue band:
$16.4 \leq \log\,[M_{GUT}] \leq 20.1$

Full model

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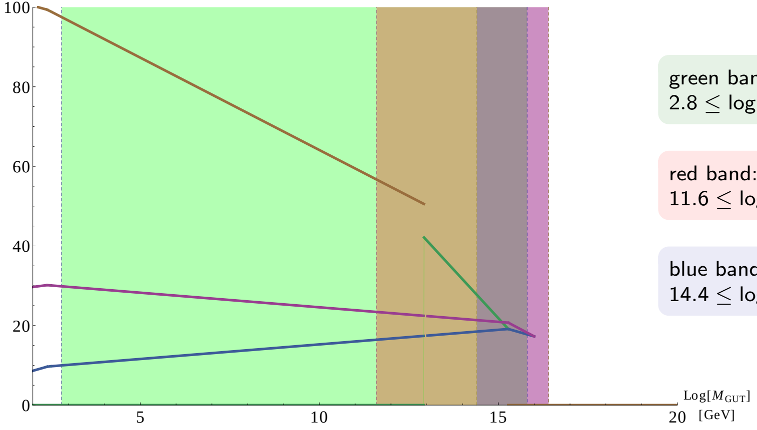
Higgs field content

Full $SO(10)$ representations : **10** ; **16** ; $\overline{\mathbf{16}}$; **45**



green band:
$2.8 \leq \log[M_{L\text{-}R}] \leq 15.8$

red band:
$11.6 \leq \log[M_{PS}] \leq 16.4$

blue band:
$14.4 \leq \log[M_{GUT}] \leq 16.4$

E_6 inspired Flavour triplet model

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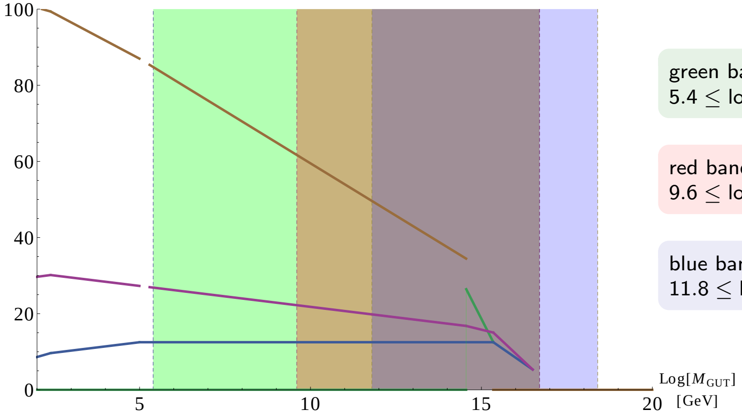
Higgs and matter field content

Full $E_6 \otimes SU(3)_F$ representations : $(\mathbf{27}, \mathbf{3})$; $(\mathbf{78}, \mathbf{1})$



green band:
$5.4 \leq \log\left[M_{L\text{-}R}\right] \leq 16.7$

red band:
$9.6 \leq \log\left[M_{PS}\right] \leq 16.7$

blue band:
$11.8 \leq \log\left[M_{GUT}\right] \leq 18.4$

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Aim of Flavour Models

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Flavour symmetry

$$\mathscr{L}_{\text{Yuk}} = -\tfrac{c}{M^n}\,\Phi_{ij}\,h\;\Psi^L_i\,\Psi^{cR}_j \qquad > M \sim M_{\text{Planck}}$$

$$\to -\tfrac{c}{M^n}\langle\Phi_{ij}\rangle\,h\,\Psi^L_i\;\Psi^{cR}_j \qquad < M$$

with the SM-Yukawa-coupling $y_{ij} = -\frac{c}{M^n}\langle\Phi_{ij}\rangle$ and $\Phi_{ij} = \prod_k^n \phi_k$

(1) following form fits quark-data quite well

$$Y_{u/d} \approx \begin{pmatrix} 0 & O(\epsilon^3) & O(\epsilon^3) \\ O(\epsilon^3) & O(\epsilon^2) & O(\epsilon^2) \\ O(\epsilon^3) & O(\epsilon^2) & O(1) \end{pmatrix} m_t$$

with $\epsilon_u \approx 0.05$ and $\epsilon_d \approx 0.15$

Roberts, Romanino, Ross, Velasco-Sevilla: arXiv:hep-ph/0104088

(2) neutrino-data also described in case of Sequential Right-Handed Neutrino Dominance (SRHND)

King: arXiv:hep-ph/0310204

Three Higgs Generations

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- consider Flavour-$SU(3)_F \otimes$ Pati-Salam GUT
- take Higgs as Flavour-triplet

$\Rightarrow$ consistent with matter-Higgs-unification:
$\rightsquigarrow$ $\Psi = (\mathbf{27}, \mathbf{3})$ (E_6-unification)

Caution: new trivial invariant $\varepsilon^{ijk}\ \Psi_i^L\, \Psi_j^R\, h_k$

$\rightsquigarrow$ large off-diagonal Yukawa matrix entries

$\Rightarrow$ Additional discrete symmetry needed

Considered flavon representations

Case 1: $\phi_i \to \mathbf{3}\ /\ \overline{\mathbf{3}}$
Case 2: $\phi_i \to \overline{\mathbf{10}} = (\overline{\mathbf{3}} \otimes \overline{\mathbf{3}} \otimes \overline{\mathbf{3}})_s$

Model of triplet Flavons

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Ansatz

- consider $SU(3) \otimes PS$-model with Flavour triplet Higgs (for singlet Higgs equivalent to existing models) King, Ross: arXiv:hep-ph/0307190
- flavons are Flavour triplets
  $\Rightarrow \langle \phi \rangle_3 = \langle \bar{\phi}_3 \rangle = (0, 0, 1)\, M \quad ; \quad \langle \phi_{23} \rangle = \langle \bar{\phi}_{23} \rangle = (0, \epsilon, \pm\epsilon)\, M$
- discrete symmetries $(U(1) \otimes Z_2)$
  $\rightarrow$ set new quantum numbers

Results:

- leading order in flavon insertion
  $\Rightarrow$ generates Yukawa 2-3 block
- NLO leads to large corrections to Yukawa matrix
- only possible to forbid field-configurations (not invariants)
  $\rightarrow$ fine tuning

$\Rightarrow$ possible, but fine-tuning or more flavons needed

work in progress

Model with decuplet flavons

Field	$SU(3)_F$	PS	$U(1)$
Ψ	$\mathbf{3}$	$(4,2,1)$	1
Ψ^c	$\mathbf{3}$	$(\bar{4},1,2)$	1
h	$\mathbf{3}$	$(1,2,2)$	1
$\bar{\phi}_1$	$\overline{\mathbf{10}}$	$(1,1,1)$	-3
$\bar{\phi}_2$	$\overline{\mathbf{10}}$	$(1,1,1)$	-3
$\bar{\phi}_3$	$\overline{\mathbf{10}}$	$(1,1,1)$	-3
H_u	$\mathbf{3}$	$(\bar{4},1,2)$	2
H_d	$\overline{\mathbf{3}}$	$(4,1,2)$	-2

$$\begin{aligned} \langle\bar{\phi}_1\rangle_{333} &\approx M \\ \langle\bar{\phi}_2\rangle_{223} &\approx \epsilon^2 M \\ \langle\bar{\phi}_2\rangle_{233} &\approx \epsilon^2 M \\ \langle\bar{\phi}_3\rangle_{123} &\approx \epsilon^3 M \\ \langle\bar{\phi}_3\rangle_{133} &\approx \epsilon^3 M \end{aligned}$$

$$W_{\text{lead}} = \sum_{i=1}^{3} \frac{y_i}{M} \Psi \Psi^c h \bar{\phi}_i$$

$$Y^f_{\text{lead}} \sim \begin{pmatrix} 0 & \epsilon^3 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

- no next to leading order contributions

Potential and vacuum alignment

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- introduce P_i to align vevs
- D-term leads to $\langle\bar{\phi}_1\rangle \sim \langle\bar{\phi}_2\rangle \sim \langle\bar{\phi}_3\rangle$
- $\mathbf{10}_i$ to guarantee D-term flatness
  $\rightsquigarrow$ assign same vev to $\mathbf{10}$
  $\rightsquigarrow$ additional sub-leading terms

$$W_{\overline{10}} = \frac{c}{M} P_1\, \phi_1\, \phi_2\, \phi_3$$

$$W_{Ren} = \sum_{i,j}^{3} P_{i+1}\left(\bar{\phi}_i \phi_j - \mu_i\right)$$

Field	$SU(3)_F$	PS	$U(1)$
ϕ_1	$\mathbf{10}$	$(1,1,1)$	5
ϕ_2	$\mathbf{10}$	$(1,1,1)$	1
ϕ_3	$\mathbf{10}$	$(1,1,1)$	6
P_1	$\mathbf{1}$	$(1,1,1)$	9
P_2	$\mathbf{1}$	$(1,1,1)$	-2
P_3	$\mathbf{1}$	$(1,1,1)$	2
P_4	$\mathbf{1}$	$(1,1,1)$	-3

- $F_{\overline{10}}$ not sufficient
- vevs can be chosen diagonal
  $\rightsquigarrow$ $\phi_i\, \overline{\phi_j} = 0\,,\, i \neq k$
- $F_{P_{i+1}} \sim \phi_i \bar{\phi}_i - \mu_i = 0$
  $\rightsquigarrow$ hierarchy of the vevs

Majorana mass matrix

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$$W_{\text{Maj}} = \frac{1}{M^3}\Psi^{c\,2} H_d^2 \left(\tilde{C}_1\,\overline{\phi}_1\phi_1 + \tilde{C}_2\,\overline{\phi}_1\phi_2 + \tilde{C}_3\,\overline{\phi}_1\phi_3 + \tilde{C}_4\,\overline{\phi}_2\overline{\phi}_2 \right)$$

$$M_{\text{Maj}} \sim \begin{pmatrix} -c_8\,\epsilon_\nu^4 & c_3\,\epsilon_\nu^3 & (c_3 - c_7)\,\epsilon_\nu^3 \\ c_3\,\epsilon_\nu^3 & c_2\,\epsilon_\nu^2 & (c_2 - c_6)\,\epsilon_\nu^2 \\ (c_3 - c_7)\,\epsilon_\nu^3 & (c_2 - c_6)\,\epsilon_\nu^2 & (c_1 + c_4 - c_5) \end{pmatrix} \frac{\langle H_d \rangle^2}{M}$$

$\Rightarrow$ Eigenvalues of order: $\left(1\,,\ \epsilon_\nu^2\,,\ \epsilon_\nu^4\right)$

$\rightsquigarrow$ sequential dominance

$\Rightarrow$ Eigenvectors: unit vectors up to corrections of order ϵ^2

$\rightsquigarrow$ near tri-bimaximal lepton mixing

Conclusions

Multi-step breaking of SUSY-Pati-Salam

- unification of gauge-couplings possible
- introduction of intermediate L-R-scale
- explanation for the low scale of light triplets
- M_{LR} and M_{PS} can vary over quite large mass-ranges

Flavour triplet Higgs models

- models with $SU(3)_F$ and Flavour triplet Higgs are possible
- model with triplet flavons are challenging but possible
- decuplet flavons reproduce Flavour structure
- only single $U(1)$ needed

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Thanks for your attention!