Pati-Salam GUT-Flavour Models with Three Higgs Generations

Florian Hartmann

in collaboration with

Wolfgang Kilian and Karsten Schnitter

based on:

JHEP **1405** (2014) 064 and arXiv:1405.1901

Universität Siegen
Theoretische Physik I

SUSY14
Manchester, July 24th, 2014

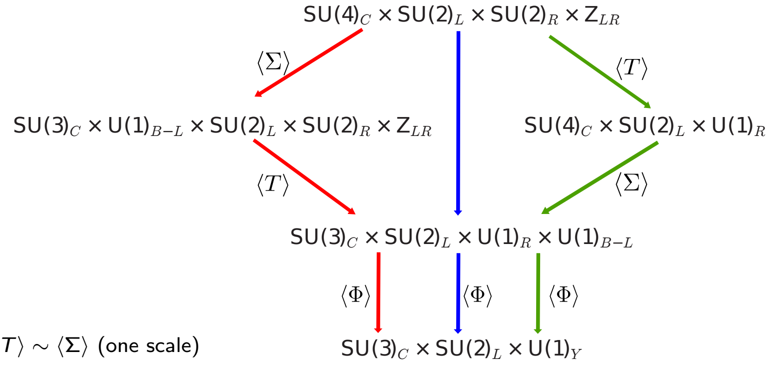
UNIVERSITÄT SIEGEN

Naturwissenschaftlich Technische Fakultät

Motivation

- Consider SUSY Pati-Salam models
  - multi-step breaking, intermediate mass scales
- include 3 generations of MSSM-Higgs doublets
  - consistent with matter-Higgs unification
- embed flavour via flavour symmetry breaking
  - theory of flavour near the Planck scale
  - single $SU(3)_F$ spontaneously broken by flavons
  - consider different flavon representations

Multi-step breaking of SUSY Pati-Salam



Class:

- A: $\langle\Phi\rangle \sim \langle T\rangle \sim \langle\Sigma\rangle$ (one scale)
- B: $\langle\Phi\rangle \ll \langle T\rangle \ll \langle\Sigma\rangle$ (three scales)
- C: $\langle\Phi\rangle \ll \langle\Sigma\rangle \ll \langle T\rangle$ (three scales)
- D: $\langle\Phi\rangle \ll \langle T\rangle \sim \langle\Sigma\rangle$ (two scales)
- E: $\langle\Phi\rangle \ll \langle\Sigma\rangle$ and $\langle T\rangle = 0$ (two scales)
- F: $\langle\Phi\rangle \ll \langle T\rangle$ and $\langle\Sigma\rangle = 0$ (two scales)

PS Higgs content

PS: $\left(SU(4)_C, SU(2)_L, SU(2)_R\right)$ $SO(10)$

Breaking to Intermediate Symmetry

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

} $\mathbf{45}$

Breaking to $SU(3)_C \times SU(2)_L \times U(1)_Y$

$\Phi_R = (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2})$ and $\overline{\Phi}_R = (\mathbf{4}, \mathbf{1}, \mathbf{2})$ to break PS
$\Phi_L = (\mathbf{4}, \mathbf{2}, \mathbf{1})$ and $\overline{\Phi}_L = (\overline{\mathbf{4}}, \mathbf{2}, \mathbf{1})$

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

optional MSSM Higgs

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

} $\mathbf{10}$

Higgs superpotential

UNIVERSITÄT SIEGEN

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

Results

- see-saw-like mass terms in Higgs fields
  - new intermediate mass-scale: $M_{\text{IND}} \sim \frac{\langle\Phi\rangle^2}{\langle\Sigma\rangle+\langle T\rangle}$

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

  $\rightsquigarrow$ useful for unification

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

- MSSM-Higgs doublet:

  $\langle T\rangle \neq 0$: μ-term $\sim \frac{\langle\Phi\rangle^2}{\langle T\rangle}$

  $\langle T\rangle = 0$: two massless doublets from Φ_L (at MSSM-scale)

  $\rightsquigarrow$ makes h $(1,2,2)$ optional

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

Gauge coupling unification

Requirements for unification

(1) unification condition at the LR-scale

$$\alpha_R^{-1} = \alpha_L^{-1}$$

(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

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

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

Inputs:

- MSSM-scale: 2.5 TeV
- 4 unification-requirements
- but 4 (5) mass-scales

⇒ scales are constrained but not fixed

Scan of field configurations

UNIVERSITÄT SIEGEN

- For each breaking class
  - scan all allowed field configurations
  - each field may appear 0, 1 or 3 times
- For each configuration
  - test whether unification below $10^{19}\,\mathrm{GeV}$ possible
  - find allowed ranges for all mass scales

Scan of field configurations

UNIVERSITÄT SIEGEN

- For each breaking class
  - scan all allowed field configurations
  - each field may appear 0, 1 or 3 times
- For each configuration
  - test whether unification below $10^{19}\,\mathrm{GeV}$ possible
  - find allowed ranges for all mass scales

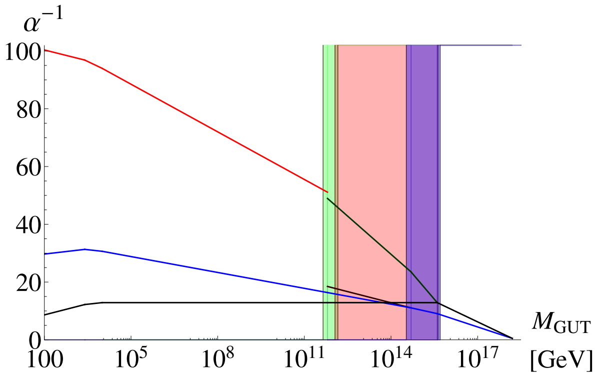
	class B	class C	class E	class F	$\sum$
scanned	144	144	324	216	828
GCU	18	57	254	29	358
$M_{\mathrm{GUT}} > 10^{16}\,\mathrm{GeV}$	18	57	131	29	235
$M_{\mathrm{IND}} < 10\,\mathrm{TeV}$ and $M_{\mathrm{GUT}} > 10^{16}\,\mathrm{GeV}$	8	34	72	0	114
$M_{\mathrm{LR}} < 100\,\mathrm{TeV}$	1	11	108	0	120
$10^{12}\,\mathrm{GeV} < M_{N_R} < 10^{14}\,\mathrm{GeV}$	16	42	123	3	184
$M_{\mathrm{IND}} \in [0.1, 10]\, \frac{v_\Phi^2}{v_\Sigma + v_T}$	14	20	203	26	263

Class B: $\langle\Phi\rangle \ll \langle T\rangle \ll \langle\Sigma\rangle$

UNIVERSITÄT SIEGEN

Field Content

	h	F	$\Phi_{L/R}$	$\overline{\Phi}_{L/R}$	Σ	E	$T_{L/R}$
PS	$(1,2,2)$	$(6,1,1)$	$(4,2,1)_{L/R}$	$(\overline{4},2,1)_{L/R}$	$(15,1,1)$	$(6,2,2)$	$(1,3,1)_{L/R}$
#	3	3	1	1	3	0	1



$M_{\rm IND} = 10^4$ GeV
$M_{\rm GUT} = 10^{18.2}$ GeV

green band [GeV]:
$7\cdot 10^{11} \leq M_{\rm MSSM} \leq 1\cdot 10^{12}$

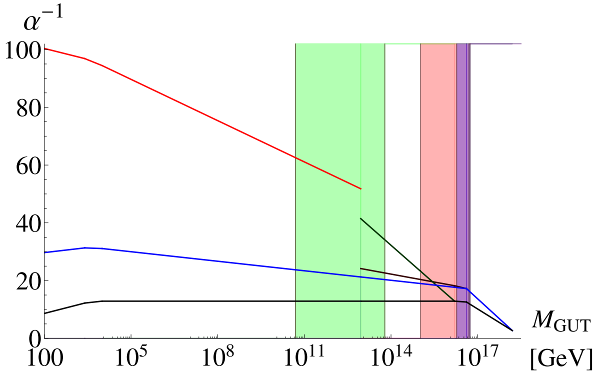
red band [GeV]:
$2\cdot 10^{13} \leq M_{\rm LR} \leq 2\cdot 10^{14}$

blue band [GeV]:
$3\cdot 10^{15} \leq M_{\rm PS} \leq 4\cdot 10^{15}$

UNIVERSITÄT SIEGEN

Field Content

	h	F	$\Phi_{L/R}$	$\overline{\Phi}_{L/R}$	Σ	E	$T_{L/R}$
PS	$(1,2,2)$	$(6,1,1)$	$(4,2,1)_{L/R}$	$(\bar{4},2,1)_{L/R}$	$(15,1,1)$	$(6,2,2)$	$(1,3,1)_{L/R}$
#	1	3	1	1	1	3	1



$M_{\text{IND}} = 10^4$ GeV
$M_{\text{GUT}} = 10^{18.2}$ GeV

green band [GeV]:
$5 \cdot 10^{10} \leq M_{\text{MSSM}} \leq 6 \cdot 10^{13}$

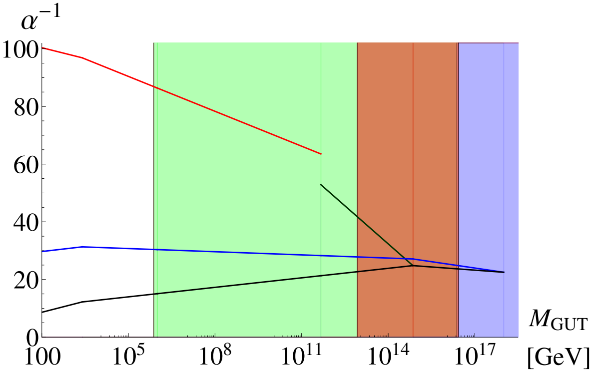
red band [GeV]:
$1 \cdot 10^{15} \leq M_{\text{QL}} \leq 5 \cdot 10^{16}$

blue band [GeV]:
$2 \cdot 10^{16} \leq M_{\text{PS}} \leq 6 \cdot 10^{16}$

Class E: $\langle T \rangle \equiv 0$

Field Content

	h	F	$\Phi_{L/R}$	$\overline{\Phi}_{L/R}$	Σ	E	$T_{L/R}$
PS	$(1,2,2)$	$(6,1,1)$	$(4,2,1)_{L/R}$	$(\bar{4},2,1)_{L/R}$	$(15,1,1)$	$(6,2,2)$	$(1,3,1)_{L/R}$
#	0	0	1	1	1	0	0



$3 \cdot 10^3 \leq M_{\mathrm{IND}} \leq 2 \cdot 10^{16}$

green band [GeV]:
$8 \cdot 10^8 \leq M_{\mathrm{LR}} \leq 2 \cdot 10^{16}$

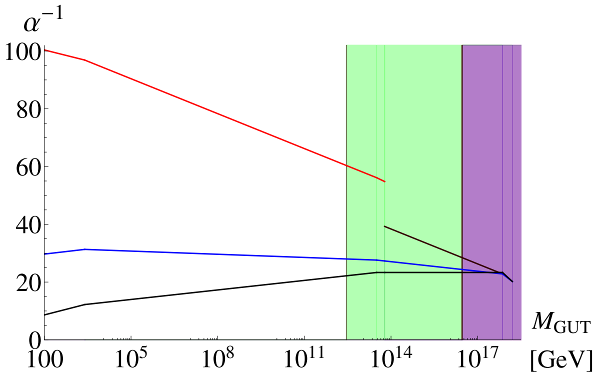
red band [GeV]:
$8 \cdot 10^{13} \leq M_{\mathrm{PS}} \leq 3 \cdot 10^{16}$

blue band [GeV]:
$3 \cdot 10^{16} \leq M_{\mathrm{GUT}} \leq 1 \cdot 10^{19}$

Class F: $\langle \Sigma \rangle \equiv 0$

Field Content

	h	F	$\Phi_{L/R}$	$\overline{\Phi}_{L/R}$	Σ	E	$T_{L/R}$
PS	$(1,2,2)$	$(6,1,1)$	$(4,2,1)_{L/R}$	$(\overline{4},2,1)_{L/R}$	$(15,1,1)$	$(6,2,2)$	$(1,3,1)_{L/R}$
#	1	3	3	3	3	1	1



not shown [GeV]:
$6 \cdot 10^8 \leq M_{\text{IND}} \leq 3 \cdot 10^{16}$

green band [GeV]:
$3 \cdot 10^{12} \leq M_{\text{MSSM}} \leq 3 \cdot 10^{16}$

red band [GeV]:
$3 \cdot 10^{16} \leq M_{\text{QL}} \leq 9 \cdot 10^{18}$

blue band [GeV]:
$3 \cdot 10^{16} \leq M_{\text{PS}} \leq 1 \cdot 10^{19}$

Aim of flavour models

Flavour symmetry broken by flavons ϕ_k

$$\begin{aligned} \mathscr{L}_{\text{Yuk}} = & -\tfrac{c}{M^n}\,\Phi_{ij} h\;\Psi_i^L\,\Psi_j^{cR} && > M \sim M_{\text{Planck}} \\ \rightarrow & -\tfrac{c}{M^n}\langle\Phi_{ij}\rangle\, h\,\Psi_i^L\,\Psi_j^{cR} && < M \end{aligned}$$

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

Requirements:

(1) following form fits quark-data quite well

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

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

- consider flavour-$SU(3)_F$ in Pati-Salam GUT
- consider 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

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

Model 1: triplet flavons

UNIVERSITÄT SIEGEN

Ansatz

- consider $SU(3) \otimes PS$-model with flavour triplet Higgs (for singlet Higgs similar to existing models) King, Ross: arXiv:hep-ph/0307190
- Flavons are flavour triplets
  $\Rightarrow \langle \phi_3 \rangle = \langle \overline{\phi}_3 \rangle = (0, 0, \sqrt[3]{\epsilon})\, M \quad ; \quad \langle \phi_{23} \rangle = \langle \overline{\phi}_{23} \rangle = (0, \epsilon, \epsilon)\, M$
- additional symmetry: $U(1) \otimes Z_3$

Results:

- leading contribution from dim 6 term $(\Psi_L \overline{\phi}_3)(\Psi_R \overline{\phi}_3)(h \overline{\phi}_3)$
- dim 6 generates Yukawa 2-3 block $(\phi_3 \to \phi_{23})$
- NLO leads to large corrections to Yukawa matrix
- only possible to forbid field-configurations (not invariants)
  $\to$ fine tuning
- possible, but need to eliminate formally leading terms

Model 2: decuplet flavons

Field	$SU(3)_F$	PS	Z_4	Z_2^R
Ψ_L	$\mathbf{3}$	$(4,2,1)$	1	$-$
Ψ_R	$\mathbf{3}$	$(\overline{4},1,2)$	1	$-$
h	$\mathbf{3}$	$(1,2,2)$	1	$+$
ϕ_3	$\overline{\mathbf{10}}$	$(1,1,1)$	1	$+$
ϕ_2	$\overline{\mathbf{10}}$	$(1,1,1)$	1	$+$
$\overline{\phi}_3$	$\mathbf{10}$	$(1,1,1)$	3	$+$
$\overline{\phi}_2$	$\mathbf{10}$	$(1,1,1)$	0	$+$
Φ_R	$\overline{\mathbf{3}}$	$(4,1,2)$	1	$+$

$$\langle\phi_3\rangle_{333} = \langle\overline{\phi}_3\rangle_{333} \sim \epsilon$$

$$\langle\phi_2\rangle_{ijk} = \langle\overline{\phi}_2\rangle_{ijk} \sim \epsilon^3 \ (i,j,k\geq 2)$$

$$\langle h\rangle = (1,1,1)\, v_{\mathrm{MSSM}}$$

$$\langle\Phi_R\rangle = (0,0,1)\, v_\Phi$$

$$Y^f_{4\&5} \sim \begin{pmatrix} 0 & \epsilon^3 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

$$W_{\mathrm{lead}} \sim \frac{1}{M}\left[\phi_3\, \Psi_L\, \Psi_R\, h + \phi_2\, \Psi_L\, \Psi_R\, h\right]$$

$$W_{\mathrm{dim5}} \sim \frac{1}{M^2}\left[h\,\phi_3\,\overline{\phi}_2\,\Psi_L\,\Psi_R + h\,\phi_2\,\overline{\phi}_2\,\Psi_L\,\Psi_R\right]$$

Majorana mass matrix

$$W_{\text{Maj}} \sim \frac{1}{M'} \left(\Psi_R \, \Phi_R\right)^2 \Big[1 + \frac{1}{M'^2} \left(\phi_3 \, \overline{\phi}_3 + \phi_2 \, \overline{\phi}_3 + \overline{\phi}_2 \, \overline{\phi}_2\right) + \frac{1}{M'^3} \left(\phi_3 \, \overline{\phi}_2 \, \overline{\phi}_3 + \phi_2 \, \overline{\phi}_3 \overline{\phi}_2\right) \Big]$$

$$M_{\text{Maj}} \sim \begin{pmatrix} \epsilon_\nu^6 & \epsilon_\nu^7 & \epsilon_\nu^5 \\ \epsilon_\nu^7 & \epsilon_\nu^4 & \epsilon_\nu^4 \\ \epsilon_\nu^5 & \epsilon_\nu^4 & 1 \end{pmatrix} \frac{\langle \phi_R \rangle^2}{M'}$$

- Eigenvalues of order: $\left(\epsilon_\nu^6 \, : \, \epsilon_\nu^4 \, : \, 1\right)$

$\rightsquigarrow$ sequential dominance

- different expansion parameter $\epsilon_\nu < \epsilon_u$

$\rightsquigarrow$ PMNS-like lepton mixing

Conclusions

Multi-step breaking of SUSY-Pati-Salam

- unification of gauge-couplings possible
- introduction of intermediate scale
  - ⇝ intermediate neutrino scale
- mass scales can vary over quite large mass-ranges

Flavour triplet Pati-Salam Higgs models

- models with $SU(3)_F$ and flavour triplet Higgs are possible
- decuplet flavons reproduce flavour structure
- triplet flavons are challenging but possible

Backup slides

Single right handed neutrino dominance

King: arXiv:hep-ph/0310204

2-D Example

$$M_{RR} = \begin{pmatrix} Y & 0 \\ 0 & X \end{pmatrix} \quad \text{and} \quad M_{LR} = \begin{pmatrix} e & b \\ f & c \end{pmatrix}$$

with: $X \gg Y$

and see-saw $M_{LL} = M_{LR} \cdot M_{RR}^{-1} \cdot M_{LR}$

$$\Rightarrow M_{LL} = \begin{pmatrix} \frac{e^2}{Y} + \frac{b^2}{X} & \frac{ef}{Y} + \frac{bc}{X} \\ \frac{ef}{Y} + \frac{bc}{X} & \frac{f^2}{Y} + \frac{c^2}{X} \end{pmatrix} \approx \begin{pmatrix} \frac{e^2}{Y} & \frac{ef}{Y} \\ \frac{ef}{Y} & \frac{f^2}{Y} \end{pmatrix}$$

$\Rightarrow$ $m_1 \approx 0$ and $m_2 \approx \frac{e^2+f^2}{Y}$

$\Rightarrow$ $\tan(\theta_{23}) \approx \frac{e}{f}$