Gauged Flavour-Symmetries in SU(5) and Pati-Salam: Part I

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Outline

- Motivation
- Construction and Anomalies
- Low-energy Yukawa sector
- Conclusion

Motivation

SM exhibits flavour symmetry

$$G_{\rm F} = \underbrace{\mathrm{SU}(3)_q^3 \times \mathrm{SU}(3)_\ell^2 \times \mathrm{U}(1)_{\rm PQ} \times \mathrm{U}(1)_{E_R}}_{\text{broken by Yukawas}} \times \mathrm{U}(1)_B \times \mathrm{U}(1)_L \times \mathrm{U}(1)_Y$$

- Why is flavour structure as observed? $\rightarrow$ symmetry principle?
- FV-NP at the TeV-scale highly constrained
- Principle of minimal flavour violation (MFV): Yukawas as spurions of broken flavour symmetry

Motivation

SM exhibits flavour symmetry

$$G_{\rm F} = \underbrace{\mathrm{SU}(3)_q^3 \times \mathrm{SU}(3)_\ell^2 \times \mathrm{U}(1)_{\rm PQ} \times \mathrm{U}(1)_{E_R}}_{\text{broken by Yukawas}} \times \mathrm{U}(1)_B \times \mathrm{U}(1)_L \times \mathrm{U}(1)_Y$$

Grinstein, Redi, Villadoro [GRV: JHEP 04(2011)043]

- Gauged flavour symmetry
- New fermions, new scalar fields (flavons)
- Yukawas non-trivially related to the vevs of the flavons

Can we embed this idea in a GUT model? $\rightarrow$ two approaches

- Pati-Salam (PS): [Feldmann, Hartmann, Kilian, Luhn 2015; Feldmann, Luhn, Moch 2016]
- Georgi-Glashow (GG): [Feldmann 2011] (new paper in prep.)

Basics

GG | PS

- Gauge Group

$\mathrm{SU}(5)$ | $\mathrm{SU}(4) \times \mathrm{SU}(2) \times \mathrm{SU}(2)'$

- Basic fermion representations

$\overline{\mathbf{10}} \supset u_R, Q_L^c, e_R$
$\mathbf{5} \supset d_R, \ell_L^c$
$\mathbf{1} \supset \nu_R$

$\bar{q}_L \sim (\bar{\mathbf{4}}, \mathbf{2}, \mathbf{1}) \supset \overline{Q}_L, \bar{\ell}_L$
$\updownarrow \mathbb{Z}_2$
$q_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}) \supset u_R, d_R, e_R, \nu_R$

- Flavour Gauge Group

$\mathrm{SU}(3)_{10} \times \mathrm{SU}(3)_5 \times \mathrm{SU}(3)_1$ | $\mathrm{SU}(3)_{\mathrm{I}} \times \mathrm{SU}(3)_{\mathrm{II}}$

Fermions in PS

Transformations under $\left[SU(4) \times SU(2) \times SU(2)'\right] \times \left[SU(3)_{\mathrm{I}} \times SU(3)_{\mathrm{II}}\right]$:

- SM-like Fermions (+ right-handed Neutrinos):

$$\bar{q}_L \sim (\bar{4}, 2, 1)(\bar{3}, 1) \overset{\mathbb{Z}_2}{\leftrightarrow} q_R \sim (4, 1, 2)(1, 3)$$

- Heavy Partner Fermions:

$$\bar{\Sigma}_L \sim (\bar{4}, 1, 2)(1, \bar{3}) \overset{\mathbb{Z}_2}{\leftrightarrow} \Xi_R \sim (4, 2, 1)(3, 1)$$

$$\bar{\Xi}_L \sim (\bar{4}, 2, 1)(1, \bar{3}) \overset{\mathbb{Z}_2}{\leftrightarrow} \Sigma_R \sim (4, 1, 2)(3, 1)$$

- Majorana Neutrinos:

$$\bar{\Theta}_L \sim (1, 1, 1)(\bar{3}, 8) \overset{\mathbb{Z}_2}{\leftrightarrow} \Theta_R \sim (1, 1, 1)(8, 3)$$

Fermions in PS

Cancellation of SU(4) Anomalies:

- SM-like Fermions (+ right-handed Neutrinos):

$$\bar{q}_L \sim (\bar{4}, 2, 1)(\bar{3}, 1) \overset{\mathbb{Z}_2}{\leftrightarrow} q_R \sim (4, 1, 2)(1, 3)$$

- Heavy Partner Fermions:

$$\bar{\Sigma}_L \sim (\bar{4}, 1, 2)(1, \bar{3}) \overset{\mathbb{Z}_2}{\leftrightarrow} \Xi_R \sim (4, 2, 1)(3, 1)$$

$$\bar{\Xi}_L \sim (\bar{4}, 2, 1)(1, \bar{3}) \overset{\mathbb{Z}_2}{\leftrightarrow} \Sigma_R \sim (4, 1, 2)(3, 1)$$

- Majorana Neutrinos:

$$\bar{\Theta}_L \sim (1, 1, 1)(\bar{3}, 8) \overset{\mathbb{Z}_2}{\leftrightarrow} \Theta_R \sim (1, 1, 1)(8, 3)$$

Fermions in PS

Cancellation of $SU(3)_{\mathrm{I}}$ Anomalies ($SU(3)_{\mathrm{II}}$ analogous):

- SM-like Fermions (+ right-handed Neutrinos):

$$\bar{q}_L \sim (\bar{4}, 2, 1)(\bar{3}, 1) \overset{\mathbb{Z}_2}{\leftrightarrow} q_R \sim (4, 1, 2)(1, 3)$$

- Heavy Partner Fermions:

$$\bar{\Sigma}_L \sim (\bar{4}, 1, 2)(1, \bar{3}) \overset{\mathbb{Z}_2}{\leftrightarrow} \Xi_R \sim (4, 2, 1)(3, 1)$$

$$\bar{\Xi}_L \sim (\bar{4}, 2, 1)(1, \bar{3}) \overset{\mathbb{Z}_2}{\leftrightarrow} \Sigma_R \sim (4, 1, 2)(3, 1)$$

- Majorana Neutrinos:

$$\bar{\Theta}_L \sim (1, 1, 1)(\bar{3}, 8) \overset{\mathbb{Z}_2}{\leftrightarrow} \Theta_R \sim (1, 1, 1)(8, 3)$$

Fermions in GG

Transformations under $[SU(5)] \times [SU(3)_{10} \times SU(3)_5 \times SU(3)_1]$:

- SM-like Fermions (+ right-handed Neutrinos):

$(\overline{10})(\bar{3}, 1, 1)$ $(5)(1, 3, 1)$ $(1)(1, 1, \bar{3})$

- Heavy Partner Fermions:

$(\overline{10})(3, 1, 1)$ $(5)(3, 1, 1)$ $(1)(\bar{3}, 1, 1)$

$(10)(3, 1, 1)$ $(\bar{5})(1, \bar{3}, 1)$ $(1)(1, 1, 3)$

Fermions in GG

Cancellation of SU(5) Anomalies:

- SM-like Fermions (+ right-handed Neutrinos):

$(\overline{10})(\bar{3}, 1, 1) \quad (5)(1, 3, 1) \quad (1)(1, 1, \bar{3})$

- Heavy Partner Fermions:

$(\overline{10})(3, 1, 1) \quad (5)(3, 1, 1) \quad (1)(\bar{3}, 1, 1)$

$(10)(3, 1, 1) \quad (\bar{5})(1, \bar{3}, 1) \quad (1)(1, 1, 3)$

Fermions in GG

Cancellation of $SU(3)_1$ Anomalies ($SU(3)_5$ analogous):

- SM-like Fermions (+ right-handed Neutrinos):

$(\overline{10})(\bar{3},1,1)$ $(5)(1,3,1)$ $(1)(1,1,\bar{3})$

- Heavy Partner Fermions:

$(\overline{10})(3,1,1)$ $(5)(3,1,1)$ $(1)(\bar{3},1,1)$

$(10)(3,1,1)$ $(\bar{5})(1,\bar{3},1)$ $(1)(1,1,3)$

Fermions in GG

Cancellation of $SU(3)_{10}$ Anomalies

- SM-like Fermions (+ right-handed Neutrinos):

$(\overline{10})(\bar{3},1,1) \quad (5)(1,3,1) \quad (1)(1,1,\bar{3})$

- Heavy Partner Fermions:

$(\overline{10})(3,1,1) \quad (5)(3,1,1) \quad (1)(\bar{3},1,1)$

$(10)(3,1,1) \quad (\bar{5})(1,\bar{3},1) \quad (1)(1,1,3)$

$\Rightarrow$ Mismatch $\lightning$

Fermions in GG

Cancellation of $SU(3)_{10}$ Anomalies

- SM-like Fermions (+ right-handed Neutrinos):

$(\overline{10})(\bar{3},1,1)$ $(5)(1,3,1)$ $(1)(1,1,\bar{3})$

- Heavy Partner Fermions:

$(\overline{10})(3,1,1)$ $(5)(3,1,1)$ $(1)(\bar{3},1,1)$

$(10)(3,1,1)$ $(\bar{5})(1,\bar{3},1)$ $(1)(1,1,3)$

$\Rightarrow$ Introduce new $\mathbb{Z}_2$-symmetry (F-parity)

- F-odd Fermions:

$(\bar{5})(3,1,1)$ $(5)(3,1,1)$ $(24)(\bar{3},1,1)$

Flavons

GG PS

- Singlets and Triplets (flavour bi-triplets and sixplets):

$\Sigma_1 \sim (1)(3,1,3)$ $S_1 \sim (1,1,1)(\bar{3},3)$

$\Sigma_5 \sim (1)(\bar{3},3,1)$ $T_1 \sim (1,3,1)(\bar{3},3)$

$\Sigma_{10} \sim (1)(\bar{6},1,1)$ $T_1' \sim (1,1,3)(\bar{3},3)$

- Adjoints (flavour bi-triplets and sixplets):

$\Theta_5 \sim (24)(\bar{3},3,1)$ $S_{15} \sim (15,1,1)(\bar{3},3)$

$\Theta_{10} \sim (24)(\bar{6},1,1)$ $T_{15} \sim (15,3,1)(\bar{3},3)$

$T_{15}' \sim (15,1,3)(\bar{3},3)$

- Scalars for the Majorana Sector (PS only):

$S_\nu \sim (1,1,1)(6,1)$ $S_\nu' \sim (1,1,1)(1,\bar{6})$ $\Phi \sim (4,2,1)(8,1)$ $\Phi' \sim (\bar{4},1,2)(1,8)$

Flavons (cont'ed)

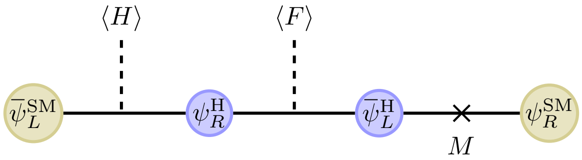
Flavour symmetry completely broken by flavon-vevs

Note:

- Did not explicitly construct scalar potential!
- Assume: vevs ✓, problematic dofs heavy
- Light ($\mathcal{O}(\mathrm{TeV})$) excitations?
- Degeneracy of down-quark- and charged-lepton-Yukawa lifted by introduction of flavons in adjoint rep.

Yukawa Lagrangian

General form of Yukawa Lagrangian:



- M: generic mass scale of $\mathcal{O}(\mathrm{TeV})$
- Only new fermions couple to flavons
- First approx.: integrate out heavy fermions $\Rightarrow$ eff. SM-Yukawas

Effective Yukawas

GG	PS
Quarks:	
$Y_u^{\text{eff}} \sim \left[\frac{1}{\tau} + \frac{1}{\sigma}\right]$	$Y_u^{\text{eff}} \sim \left[\frac{1}{(s+t')_u} + \frac{1}{s_u}\right]$
$Y_d^{\text{eff}} \sim \left[\frac{1}{t}\right]$	$Y_d^{\text{eff}} \sim \left[\frac{1}{(s+t')_d} + \frac{1}{s_d}\right]$
Charged Leptons:	
$Y_\ell^{\text{eff}} \sim \left[\frac{1}{t_\ell}\right]$	$Y_\ell^{\text{eff}} \sim \left[\frac{1}{(s+t')_\ell} + \frac{1}{s_\ell}\right]$

- $\tau, \sigma, t, s, \ldots$: linear combinations of flavon vevs, divided by M
- Inverted hierarchy of partner masses
- Similar to relations in GRV, but in general not invertible!
- Valid for $\tau, \sigma, t, s, \cdots \gg 1$ $\Rightarrow$ Problem with third gen.!

More sophisticated approach:

- Diagonalisation of 9×9-mass matrices

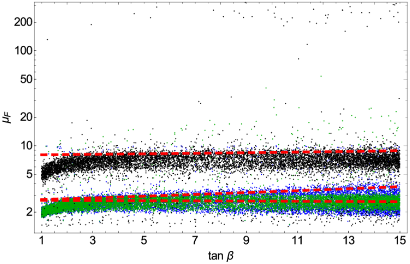
$$M_u = \begin{pmatrix} 0 & \lambda_u \epsilon_u \mathbb{1} & \mathbb{1} \\ \mathbb{1} & \tau & 0 \\ \lambda_u \epsilon_u \mathbb{1} & 0 & \sigma \end{pmatrix} M_{10} \qquad \text{etc.}$$

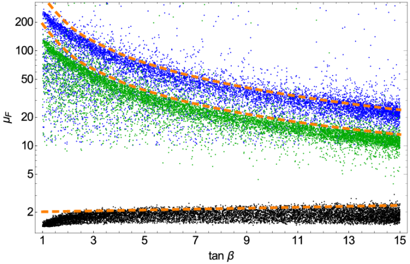
  with $\epsilon_u = v_u / M_{10}$

- Large number and hierarchies of parameters $\Rightarrow$ numerical scan

Quark partner masses in PS

- New fermion masses scale with fundamental Dirac mass M
- Normalized masses $\mu_F = m_F/M$ depend on $\tan\beta$
- Multiple solutions lead to
  two distinct patterns for 3rd generation partners:





Quark partner masses in PS

- New fermion masses scale with fundamental Dirac mass M
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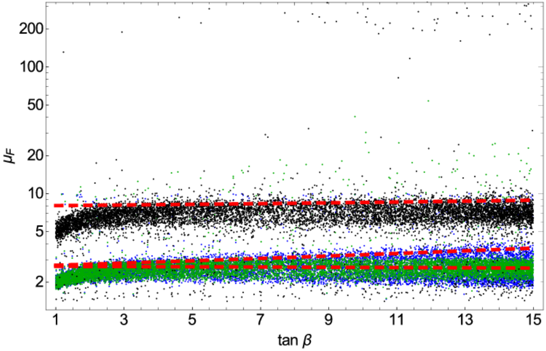
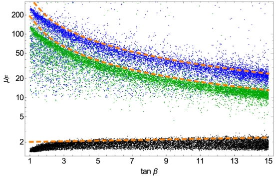
  two distinct patterns for 3rd generation partners:
  - three lighter new fermions = b', t'', b''

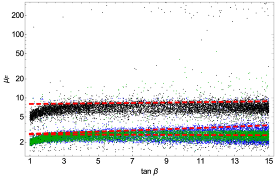


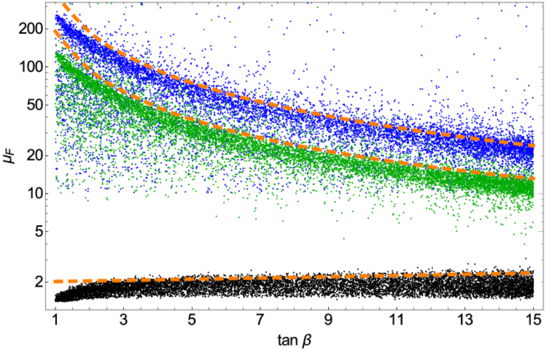


Quark partner masses in PS

- New fermion masses scale with fundamental Dirac mass M
- Normalized masses $\mu_F = m_F/M$ depend on $\tan\beta$
- Multiple solutions lead to
  two distinct patterns for 3rd generation partners:

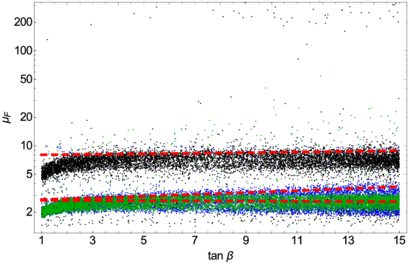
  - one lightest new fermion = top-partner t'

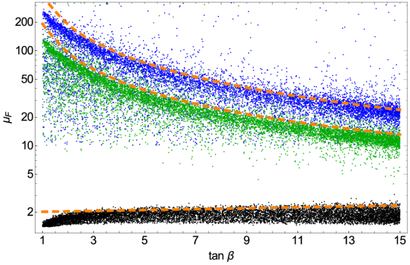




Quark partner masses in PS

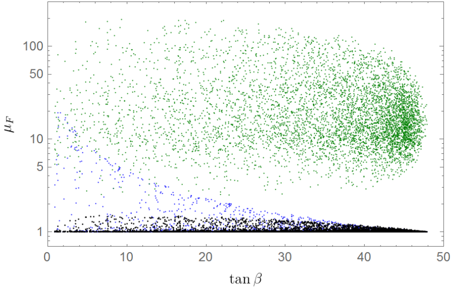
- New fermion masses scale with fundamental Dirac mass M
- Normalized masses $\mu_F = m_F/M$ depend on $\tan\beta$
- Multiple solutions lead to
  two distinct patterns for 3rd generation partners:
  - three lighter new fermions $= b', t'', b''$
  - one lightest new fermion $=$ top-partner t'





Quark partner masses in GG (with 2HDM)

- Only one class of solutions
- Again: $m_{t'} \lesssim m_{b'} < m_{t''} = m_{b''}$



- **GG and PS**: Depending on the choice of M third gen. partners can have masses in the TeV range!

Conclusion

- GUT model with spontaneously broken flavour symmetry
- New fermion(s) within reach of LHC (possibly)
- Non-trivial flavour structure, expressed via effective Yukawa couplings in low-energy limit

Open questions

- Construct scalar potential
- Effects of flavon excitations
- Effects of flavour gauge bosons (could be $\mathcal{O}(\mathrm{TeV})$ in some scenarios)

- Anomalous couplings through mixing with partners
  - GG: very small effects in low-energy quark phenomenology
  - PS: larger effects in quark and lepton phenomenology (next talk)

Thank You!

Yukawa Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\text{Yuk}} = {} \\
& M_{10}\, \overline{\mathbf{10}}_{(\bar{3}11)}\, \mathbf{10}_{(311)} + M_5\, \mathbf{5}_{(131)}\, \bar{\mathbf{5}}_{(1\bar{3}1)} + M_1\, \mathbf{1}_{(11\bar{3})}\, \mathbf{1}_{(113)} \\
& + \lambda_{10} \mathbf{10}_{(\bar{3}11)}\, \mathbf{10}_{(311)}\, \mathbf{5}_H + \lambda_5 \bar{\mathbf{5}}_{(\bar{3}11)}\, \mathbf{10}_{(311)}\, \mathbf{5}_H^\dagger + \lambda_1 \mathbf{1}_{(311)}\, \bar{\mathbf{5}}_{(\bar{3}11)}\, \mathbf{5}_H \\
& + \overline{\mathbf{10}}_{(\bar{3}11)} \left(\Sigma_{10}^\dagger + \Theta_{10}^\dagger \right) \mathbf{10}_{(\bar{3}11)} + \bar{\mathbf{5}}_{(\bar{3}11)} \left(\Sigma_5^\dagger + \Theta_5^\dagger \right) \mathbf{5}_{(131)} \\
& + \mathbf{1}_{(311)}\, \Sigma_1\, \mathbf{1}_{(11\bar{3})} + \lambda_{\text{Maj}}\, \mathbf{1}_{(311)}\, \Sigma_{10}\, \mathbf{1}_{(311)} + \text{h.c.}.
\end{aligned}
$$

- $M_{10,5,1}$: generic mass scales $\mathcal{O}(\text{TeV})$
- $\lambda_{10,5,1,\text{Maj}}$: generic couplings $\mathcal{O}(1)$
- some coupling-constants absorbed in def. of flavons
- mass of partners related to flavon vevs

References

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