Neutrino masses and LFV from minimal breaking of $U(3)^5$ and $U(2)^5$ flavor symmetries

Based on: G.B., G.Isidori, J. Jones-Perez arXiv:1204.0688

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Outline

1. Quark sector
   - MFV
   - U(2)
2. Lepton sector
   - Starting points
   - Masses and mixings
3. Slepton sector
   - LFV

Minimal Flavour Violation

SM quark sector without Yukawa interactions symmetric under

$$U(3)^3 = U(3)_u \times U(3)_d \times U(3)_Q$$

MFV hypotesis: Yukawas are the only source of breaking of $U(3)^3$

- with $Y_u = (3, \bar{3}, 1)$ and $Y_d = (3, 1, \bar{3})$ all effective operators must be $U(3)^3$ invarinat
- $(Y_u)_{33} = y_{top}$ dominates
  - flavour changing transitions suppressed in up sector
  - flavour changing transitions in down sector governed by $\lambda_{FC} = (Y_u Y_u^\dagger)_{ij} = y_{top}^2 V_{ti}^* V_{tj} \to c_{ij}$
- CKM and fermion mass suppression also in NP effects

MSSM soft terms obtained dynamically with

- **Universality** and **allignement** at high scale
- corrections $\propto Y_i$ generated by the **running** to low energy scale

D'Ambrosio, Giudice, Isidori, Strumia ('02)

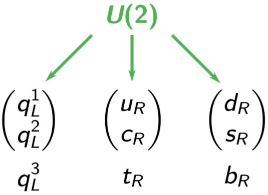
Alternatives to MFV

Main open problems in MSSM-MFV

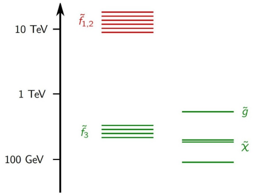
- no explanation for small **CPV flavour-conserving** observables
- no explanation for **hierarchies** in quark masses and mixings
- strong **direct bounds** for first two generations, weaker for third one

Effective SUSY → U(2)

- $y_{III gen} >> y_{I,II gen}$
- first two squark generations degenerate and heavier than the third generation (**stabilize higgs sector**)
- too **large FCNC**



Pomarol et al ('96), Barbieri et al ('96)



Cohen et al ('96), Giudice et al ('08)

Alternatives to MFV

Main open problems in MFV

- no explanation for small **CPV flavour-conserving** observables
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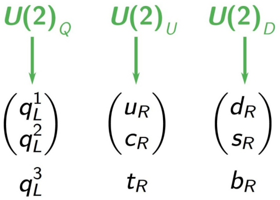
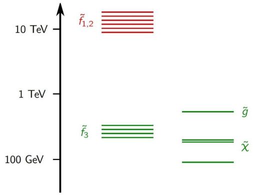
Effective SUSY → $U(2)^3$

- $y_{IIIgen} >> y_{I,IIgen}$
- first two squark generations degenerate and heavier than the third generation (**stabilize higgs sector**)
- too large FCNC → **FCNC under control**





Barbieri et al ('11)

Cohen et al ('96), Giudice et al ('08)

Breaking $U(2)^3$

$U(2)_Q \times U(2)_u \times U(2)_d \to U(1)_B$

- $V \sim (2,1,1)$
- $\Delta Y_u \sim (2,\bar{2},1)$
- $\Delta Y_d \sim (2,1,\bar{2})$

$$Y_u = y_t \begin{pmatrix} \Delta Y_u & x_t V \\ 0 & 1 \end{pmatrix}$$

$$Y_d = y_b \begin{pmatrix} \Delta Y_d & x_b V \\ 0 & 1 \end{pmatrix}$$

$$m^2_{\tilde{Q}} = m^2_{Q_h} \begin{pmatrix} 1 + c_{Qv} V^* V^T + c_{Qu} \Delta Y_u^* \Delta Y_u^T + c_{Qd} \Delta Y_d^* \Delta Y_d^T & x_Q e^{-i\phi_Q} V^* \\ x_Q e^{i\phi_Q} V^T & m^2_{Q_l}/m^2_{Q_h} \end{pmatrix}$$

$$W_L^d = \begin{pmatrix} c_d & \kappa^* & -\kappa^* s_L e^{i\gamma} \\ -\kappa & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix} \qquad (W_R^d)_{ij} \approx \delta_{ij}$$

- **New mixing** angle and new phase in **left sector**
- **MFV-like** alignment in **right sector**

Barbieri, Isidori, Jones-Perez, Lodone, Straub (1105.2296)

Including leptons

Is it possible to generalize this framework to the **lepton sector**?

Charged leptons

- **hierarchcal** masses (and mixings)
- $U(2)^3 \to U(2)^5 = U(2)^3 \times U(2)_l \times U(2)_e$

Neutrinos

- small hierarchy in masses and **large mixings** (θ_{23})
- not apparently $U(2)$ structure

Neutrino: starting points

Expanding in the experimentally **small parameters**

$$\zeta^2 = \frac{\Delta m^2_{sol}}{|\Delta m^2_{atm}|} \to 0 \qquad s_{13} \to 0$$

in charged lepton diagonal basis

$$M^2_\nu = m^\dagger_\nu m_\nu = U_{PMNS}(m^2_\nu)^{diag} U^\dagger_{PMNS}$$

$$\to m^2_{\nu_1} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \Delta m^2_{atm} \begin{pmatrix} 0 & 0 & 0 \\ 0 & s^2_{23} & s_{23}c_{23} \\ 0 & s_{23}c_{23} & c^2_{23} \end{pmatrix}$$

Starting points

$$M^2 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & s^2_{23} & s_{23}c_{23} \\ 0 & s_{23}c_{23} & c^2_{23} \end{pmatrix} \quad M^2 \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & c^2_{23} & -s_{23}c_{23} \\ 0 & -s_{23}c_{23} & s^2_{23} \end{pmatrix} \quad M^2 \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

if $m_{\nu_1} << \Delta m^2_{atm}$ **(NH)**

if $m_{\nu_1} << \Delta m^2_{atm}$ **(IH)**

if $m_{\nu_1} >> \Delta m^2_{atm}$ **(QD)**

The model

$U(3)_l \times U(3)_e \to O(2)_l \times U(2)_e$

$$m^0_\nu \sim (\mathbf{6},\mathbf{1}) \quad \to \quad m_\nu = m_{\nu_1}\left(\begin{array}{c|c} I & 0 \\ \hline 0 & 1 \end{array}\right) \quad (\mathbf{L}_L m^0_\nu \mathbf{L}_L^T)$$

$$Y^0 \sim (\mathbf{3},\bar{\mathbf{3}}) \quad \to \quad Y_e = y_\tau \left(\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right) \quad (\mathbf{L}_L Y^0 \mathbf{e}^c)$$

susy non-holomorphy makes this large breaking don't spoil the m_ν degenerancy (effective symmetries: $O(3)_l$ for neutrinos and $U(2)_l \times U(2)_e$ for charged leptons)

$O(2)_l \times U(2)_e \to /$

leading breaking $O(\epsilon = |V_{cb}| \simeq \lambda_C^2)$

$$X = \left(\begin{array}{c|c} \Delta_L & V \\ \hline V^\dagger & x \end{array}\right) \sim (\mathbf{8},\mathbf{1}) \quad \to \quad Y_e = y_\tau \left(\begin{array}{c|c} 0 & V \\ \hline 0 & 1 \end{array}\right) \quad (\mathbf{L}_L X Y^0 \mathbf{e}^c)$$

$$\to \quad m_\nu = m_{\nu_1}\left[I + a\left(\begin{array}{c|c} \Delta_L & V \\ \hline V^T & x \end{array}\right)\right] \quad (\mathbf{L}_L X m^0_\nu \mathbf{L}_L^T)$$

subleading breaking $O(\epsilon^2)$

$$\Delta\hat{Y}_e = \left(\begin{array}{c|c} \Delta Y_e & 0 \\ \hline 0 & 0 \end{array}\right) \sim (\mathbf{3},\bar{\mathbf{3}}) \quad \to \quad Y_e = y_\tau \left(\begin{array}{c|c} \Delta Y_e & V \\ \hline 0 & 1 \end{array}\right) \quad (\mathbf{L}_L X \Delta Y^0 \mathbf{e}^c)$$

Charged sector

- identical to $\mathbf{U}(\mathbf{2})^3$ *Barbieri et al*
- with a suitable $O(2)_l$ rotation we choose a basis in which $\mathbf{V}^{\mathbf{T}} \propto (\mathbf{0}, \mathbf{1})$
- the **1-2 sector** is completelly **undetermined** by the symmetry and in analogy to the quark sector we take a small misalignement in ΔY_e (and Δ_L)

$$V = \begin{pmatrix} 0 \\ x_\tau e^{i\phi_\tau} \end{pmatrix}, \quad \Delta Y_e = \begin{pmatrix} c_\tau & -s_e e^{i\alpha_e} \\ s_e e^{-i\alpha_e} & c_e \end{pmatrix} \begin{pmatrix} y_e/y_\tau & 0 \\ 0 & y_\mu/y_\tau \end{pmatrix}$$

Charged leptons diagonalization matrix

$$U_{eL} \approx \begin{pmatrix} c_e & s_e\, c_\tau\, e^{i\alpha_e} & -s_e\, s_\tau\, e^{i(\alpha_e+\phi_\tau)} \\ -s_e\, e^{-i\alpha_e} & c_e\, c_\tau & -c_e\, s_\tau\, e^{i\phi_\tau} \\ 0 & s_\tau\, e^{-i\phi_\tau} & c_\tau \end{pmatrix}$$

where in analogy wih **quark sector**

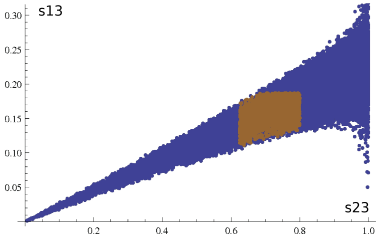
- $s_\tau = O(s_t = |V_{cb}| \simeq \lambda_C^2)$
- $s_e = O(s_d = |V_{td}|/|V_{ts}| \simeq \lambda_C)$

Neutrino predictions

Summarizing: **neutrino mass matrix**

$$m_\nu = m_{\nu_1} \begin{pmatrix} 1-\sigma\epsilon & \gamma\epsilon^2 & 0 \\ \gamma\epsilon^2 & 1-\delta\epsilon & r\epsilon \\ 0 & r\epsilon & 1 \end{pmatrix}$$

if $(\Delta_L)_{11,12,22} = 0, O(\epsilon^2), O(\epsilon)$ similar to ΔY_e



Model predictions

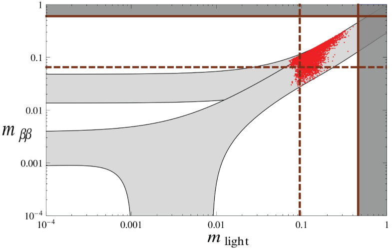
- Quasi **degenerate spectrum**

$$m_{\nu_1} = O(1)\left(\frac{\Delta m^2_{atm}}{\epsilon}\right)^{1/2} = O(0.3\,\mathrm{eV})$$

- θ_{13} in **agreement** with recent results

$$s_{13} e^{i\delta_P} = s_e s_{23} e^{\alpha_e + \pi}$$

giving $s_{13} = 0.16 \pm 0.02$ assuming $s_e = s_d = |V_{td}|/|V_{ts}|$ and the



Other neutrino observables

- Mass squared ratio need a modest finetuning (δ small)

$$\zeta^2 = \frac{2\sigma - \delta - (\delta^2 + 4r^2)^{1/2}}{2\sigma - \delta + (\delta^2 + 4r^2)^{1/2}}$$

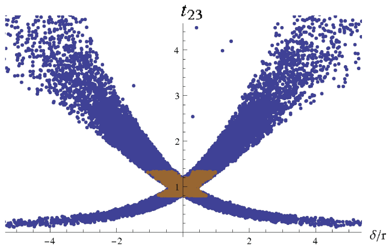
- θ_{23} is $O(1)$ and $\to \pi/4$ for $\delta \to 0$

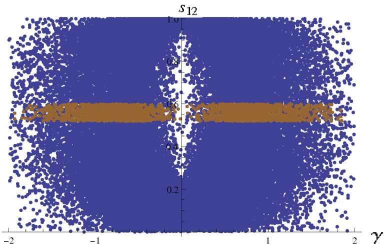
$$t_{23} = \frac{s_{23}}{c_{23}} = \frac{\delta \pm [\delta^2 + 4r^2]^{1/2}}{2r}$$

- θ_{12} is more unstable and in the limit $s_e \to 0$

$$\tan 2\theta_{12} = \frac{4\gamma\,\epsilon}{2\sigma - \delta - [\delta^2 + 4r^2]^{1/2}} c_{23} = O(1) \times \frac{\epsilon}{\zeta^2}$$

- **Inverse hierarchy** is identical with $\sigma \to -\sigma$ and $\delta \to -\delta$





Slepton mass matrix

Slepton mass matrix LL

$$\tilde{m}^2_{LL} = \left(\begin{array}{c|c} \frac{I + c_3\Delta_L + c_4 \Delta Y_e^* \Delta Y_e^T}{c_3 V^\dagger} & \frac{c_3 V}{1 + c_2 |y_\tau|^2 + c_3 x} \end{array} \right) \tilde{m}^2_L$$

$$\simeq \begin{pmatrix} 1 & c_3'' \epsilon^2 & 0 \\ c_3''^* \epsilon^2 & 1 + c_3 \epsilon & c_3' \epsilon \\ 0 & c_3'^* \epsilon & 1 + c_2 |y_\tau|^2 \end{pmatrix} \tilde{m}^2_L$$

Comparison with $U(2)^3$
Barbieri et al

- same structure off-diagonal
- light third gen if $1 + c_2|y_\tau|^2 << 1$ (finetuning)

Slepton mass matrix RR

$$\tilde{m}^2_{RR} = \left(\begin{array}{c|c} \frac{I + \tilde{c}_4 \Delta Y_e^T \Delta Y_e^*}{c_7 y_\tau V^T \Delta Y_e^*} & \frac{c_7 \Delta Y_e^T V^* y_\tau^*}{1 + |y_\tau|^2(\tilde{c}_2 + \tilde{c}_3 x)} \end{array} \right) \tilde{m}^2_R \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 + \tilde{c}_2 |y_\tau|^2 \end{pmatrix} \tilde{m}^2_R$$

Slepton mass matrix LR

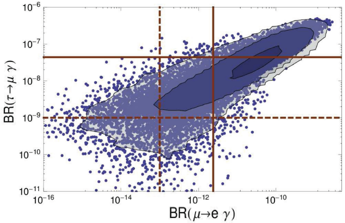
$$A_e = \left(\begin{array}{c|c} \frac{a_1 \Delta Y_e}{0} & \frac{a_2 V}{a_3} \end{array} \right) y_\tau A_0 \xrightarrow[Y_e^{diag}]{} \begin{pmatrix} a_1 \ell_1 & 0 & (a_2 - a_3) s_e e^{i\alpha_e} \epsilon \\ 0 & a_1 \ell_2 & (a_2 - a_3) c_e \epsilon \\ 0 & 0 & a_3 \end{pmatrix} y_\tau A_0$$

Lepton flavor violation (indipendent from ν sector)

- $\tilde{m}^2_{LL}$ diagonalized by

$$W^e_L = \begin{pmatrix} c_e & s_e e^{-i\alpha_e} & -s_e s^e_L e^{i\gamma} e^{-i\alpha_e} \\ -s_e e^{i\alpha_e} & c_e & -c_e s^e_L e^{i\gamma} \\ 0 & s^e_L e^{-i\gamma} & 1 \end{pmatrix}$$

- $\tilde{m}^2_{RR}$ almost diagonal
- $\tilde{m}^2_{LR}$ diagonal in 1-2 sector and suppressed in 1-2,3

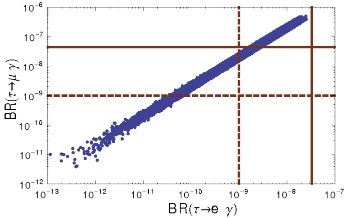


$\mu \to e\gamma$ and $\tau \to \mu\gamma$

with only dominant chargino contributions

$$\left(\frac{BR(\mu \to e\gamma)}{BR(\tau \to \mu\gamma)}\right)^{\chi^\pm} \approx 5.1\, s_e^2\, s^{e\,2}_L$$

$$\left(\frac{BR(\tau \to e\gamma)}{BR(\tau \to \mu\gamma)}\right)^{\chi^\pm} \approx s_e^2$$



see also Barbieri et al 1203.4218

Numerical scan

$m_{III} \in [200, 1000]$, $m_{I,II} \in [5, 100]\, m_{III}$, $A_0 \in [-3, 3]\, m_{I,II}$,
($\tan\beta = 10$, $M_2 = 500\text{GeV}$, $\mu = 600\text{GeV}$ in the figure)

Conclusions

- We propose a model for the **lepton sector** based on a minimal breaking of $U(3)^5$ consistent with the $U(2)^3$ model in *Barbieri et al* in the quark sector
- The key ingredient is a **two steps separate breaking**
  - $U(3)_l \to O(3)_l$: quasi degenerate neutrinos
  - $U(3)_l \times U(3)_e \to U(2)_l \times U(2)_e$: hierarchical charged fermions

  followed by a subleading breaking connecting the two sectors
- θ_{23} as a small perturbation of an approximately **degenerate spectrum**
- $\mathbf{s_{13}/s_{23} = s_e} = O(\lambda_C)$ in agreement with recent experiment
- $0\nu\beta\beta$ **decay observables** in the next generation experiments
- Extending $U(2)^3$ in the lepton sector gives **LFV** effects very close to the present limits and will be **falsified/confirmed by future experiments**

Thank you for the attention