New Approach to Flavor

R. N. Mohapatra

UNIVERSITY OF MARYLAND

Two Fundamental puzzles of SM

(i) **Origin of Mass**: two problems:

(a) quark masses : SM Higgs

(b) neutrino masses; New Higgs, New symmetries

(ii) **Origin of Flavor:**

Fermion (including neutrinos) masses, mixings, $\not{CP}$ and $\not{P}$

Crucial for understanding issues e.g. origin of matter

Understanding Flavor…

- Zero fermion masses→ SM + RH nu → flavor symmetry group:

$$U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e \times U(3)_N$$

- **Hope** is that observed flavor structure is a consequence of breaking this symmetry-
- Questions: **a) Gauge or global symmetry ?**

  b) Scale of the symmetry breaking?

  c) New dynamics of the symmetry ?

Global Flavor symmetry

- Breaking leads to massless familons
- Must decouple before BBN-
- Not seen in experiments so far-
- Limits on the scale (PDG):

$$M_H \geq 10^{10}\, GeV$$ from $\mu \rightarrow e + \chi$ decay **(Jodidio et al.)**

Similar limits from $K \rightarrow \pi + \chi$ **(Atiya et al)**

Gauged Flavor Symmetry

- **No extra fermions** → Anomaly constraints restrict gaugeable symmetries to **only vector subgroups**

$$SU(3)_{q,V}, SU(3)_{l,V}, SU(2)_V \, etc$$

- Scale of symmetry breaking set by FCNC :

$$H_{\Delta F=2} = \frac{g_H^2}{M_H^2} \bar{q}_i \Gamma q_j \bar{q}_i \Gamma q_j + h.c.$$

- $K_L - K_S, D - \overline{D}, B_S - \overline{B}_S$ imply → typically (for g_H~1)

$$M_H \geq 1000 TeV$$

(UTFIT coll. Bona et al)

Bounds on New Physics from FCNC

- Bounds on scale: $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d=6} \frac{c_{ij}^{(6)}}{\Lambda_{NP}^2} O_{ij}^{(6)}$

[Isidori, Nir, Perez '10]

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} (Λ = 1 TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d\to\psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d\to\psi K}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

- **Is the dynamics of gauged flavor then experimentally inaccessible ?**

Typical structure of these theories:

- Gauge group: $G_{SM} \times SU(3)_{H,V}$
- Sym Br. Higgs: SM H + $Y_{u,ij}$ **(Y-flavon fields)**
- $< Y_{u,ij} >$ breaks flavor sym; H breaks SM;
- Fermion masses arise from (typically) $\overline{Q}_i H u_j \frac{Y_{u,ij}}{\Lambda}$
- Implies e.g. that: $Y_{u,33} >> Y_{u,22} >> Y_{u,11}$

$$H_{\Delta F=2} \sim \frac{g_H^2}{M_H^2} \overline{q}_{i,L} \gamma^{\mu} q_{j,L} \overline{q}_{i,L} \gamma_{\mu} q_{j,L} + L \to R + ..$$

- $M_H \propto < Y_{u,ij} >$ Hence the limit on scale

New approach:

- **Use Quark seesaw:**
- **Add 3 vector like quarks** ($\psi^{u,d}$) + symmetries→seesaw mass matrices:

$$M_{q\psi} = \begin{pmatrix} 0 & m_{q_L\psi} \\ m_{q_R\psi} & M_{\psi\psi} \end{pmatrix} \rightarrow \quad m_q \cong \frac{m_{q_{L\psi}} m_{q_{R\psi}}}{M_{\psi\psi}}$$

- With left-right sym.→

$$\boxed{M_{u,ij} = v_{wk} v_R \lambda_{u,i} M^{-1}_{\psi\psi,ij} \lambda_{u,j}}$$

(Davidson, Wali'88; Babu, RNM'89)

Full Flavor Gauging

- **Advantage of seesaw approach in SM:**

  Full chiral flavor group can be anomaly free and can be gauged **(Grinstein, Redi and Villadoro'09)**

  Quark masses: $$M_{q,ij} = \lambda_q^2 v_{wk} M_{\psi_q} M_{\psi\psi,ij}^{-1}$$

- **Note: inverse mass relation between known quark and vectorlike Quark masses**
- **Flavor scale is same as vector like quark mass→**

→Flavor scale comes down to TeV range;

→New vector like quarks in the LHC range;

Basic reason for lower scale

- Inverse relation between quark and vector like masses → for Horizontal scale:

$$Y_{u,33} << Y_{u,22} << Y_{u,11}$$

$$m_t^{-1} : m_c^{-1} : m_u^{-1}$$

$$H_{\Delta F=2} = \frac{g_H^2}{M_H^2}\bar{q}_i \Gamma q_j \bar{q}_i \Gamma q_j + h.c. \Rightarrow \frac{m_u^2 V_{ij}^2}{M_\psi^2 v_{wk}^2}\bar{q}_i \Gamma q_j \bar{q}_i \Gamma q_j + h.c.$$

Huge suppression→ Much lower flavor gauge scale

Conceptual issue with SM flavor gauging

- Fermion mass protection lore: **"all fermion masses must arise from a gauge symmetry breaking-otherwise it could be of the order of Planck mass !!"**
- E.g. in QED, electron mass is not "gauge protected" in the above sense but in SM it is.
- In GRV model, $(d_R, \psi_L^d), (u_R, \psi_L^u)$ pairs have same gauge quantum numbers and get **gauge unprotected** mass.

Flavor gauging with asymptotic Parity

- Guadagnoli, Mohapatra , Sung, arXiv: 1103.4170 JHEP -2011
- LR allows **more economical flavor** gauging:

From $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e \times U(3)_N$ (SM)

to $U(3)_{Q,L} \times U(3)_{Q,R} \times U(3)_{\ell,L} \times U(3)_{\ell,R}$ (LR)

All Fermion masses gauge protected !!

(i) generates neutrino mass

(ii) Solves strong CP problem from parity

- **Two versions**: (i) TeV parity or

(ii) no parity TeV SU(2)_R

Some details: TeV parity

- Quark sector: Fermions: $Q_{L,R} + \psi_{V,L,R}$; Vectorlike quarks
- Higgs fields: LR doublets: $\chi_{L,R}$

  Flavon fields: $Y_{u,d}(3,\bar{3})$
- Yukawa couplings and fermion mass protection:
- L_Y= $\lambda_u(\bar{Q}_L\tilde{\chi}_L\psi^u_R + \bar{Q}_R\tilde{\chi}_R\psi^u_L) + \lambda_d(\bar{Q}_L\chi_L\psi^d_R + \bar{Q}_R\chi_R\psi^d_L)$

  $$+\lambda'_u\bar{\psi}^u_L Y_u\psi^u_R + \lambda'_d\bar{\psi}^d_L Y_d\psi^d_R + \text{h.c.}\ ,$$
- Symmetry breaking scales $v_{L,R}$

Flavor from symmetry breaking

- Quark mass matrices:

$$\text{Mu}= \begin{pmatrix} 0 & \lambda_u v_L \\ \lambda_u v_R & <Y_u> \end{pmatrix} \text{ ; Md}= \begin{pmatrix} 0 & \lambda_d v_L \\ \lambda_d v_R & <Y_d> \end{pmatrix}$$

$$<Y_u> = V_{CKM}^{+} \begin{pmatrix} Y_u & & \\ & Y_c & \\ & & Y_t \end{pmatrix} V_{CKM} \qquad <Y_d> = \begin{pmatrix} Y_d & & \\ & Y_s & \\ & & Y_b \end{pmatrix}$$

- New parameters: v_R, $\lambda_{u,d}$
- **All flavor consequence of symmetry breaking;**

Consequences:

- **Two new scales beyond SM**

  Right hand weak scale: v_R , Flavor scales <Y>;
- Quark seesaw → $Y_u >> Y_c >> Y_t$
- All flavor gauge boson masses determined by Y_u and quark mixings.
- **FCNC interactions given by ~** $\frac{m_u^2 V_{ij}^2}{\lambda_q^4 v_R^2 v_{wk}^2} \bar{q}_i \Gamma q_j \bar{q}_i \Gamma q_j + h.c.$

LR SCALE INPUT FOR TEV PARITY CASE

- **Low energy observables**: combination of KL-KS, epsilon, d_n together.(uncertainty long distance effetcs);
- **Parity defined as usual:**($\psi_L \leftrightarrow \psi_R$) **minimal model:** **(An,Ji,Zhang,RNM '07)**

$$M_{W_R} \geq 4TeV$$

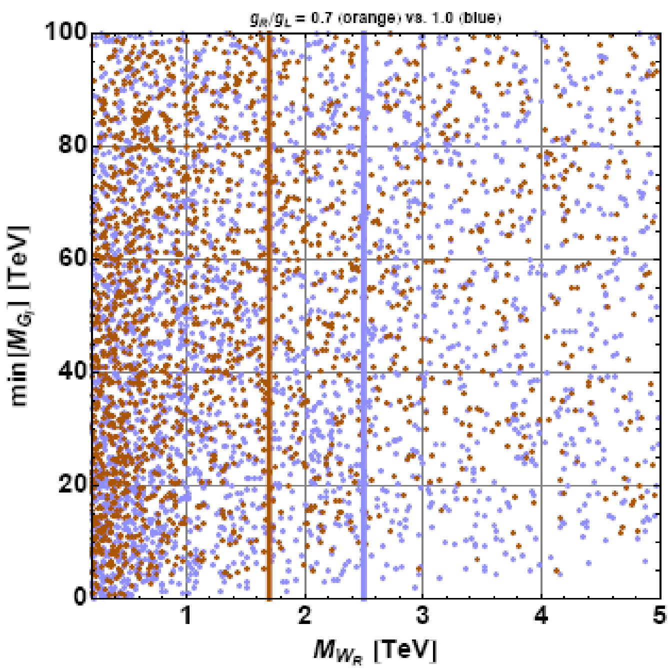
- **Parity as C (as in SUSY i.e.** $\psi \leftrightarrow \psi^c$) **(Maezza, Nemesvek, Nemevsek,Senjanovic'10)**

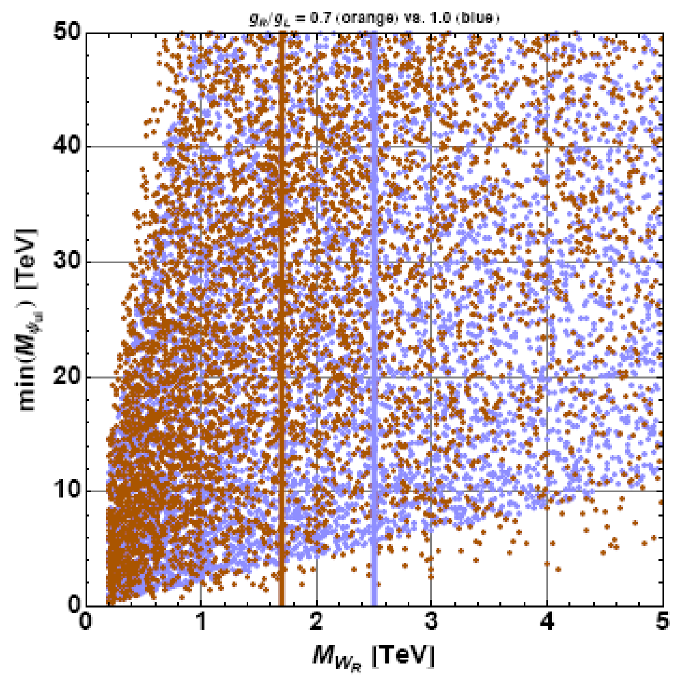
$$M_{W_R} \geq 2.5TeV$$

- **Collider (CDF,D0) 640-750 GeV; CMS- 1.7 TeV**
- **Muon decay (TWIST) 592 GeV**
- **Broken TeV parity**: $g_L \neq g_R$ **weaker bounds on MWR**

FCNC Bounds on new physics:

- Flavor and vectorlike quark masses (GMS'11)

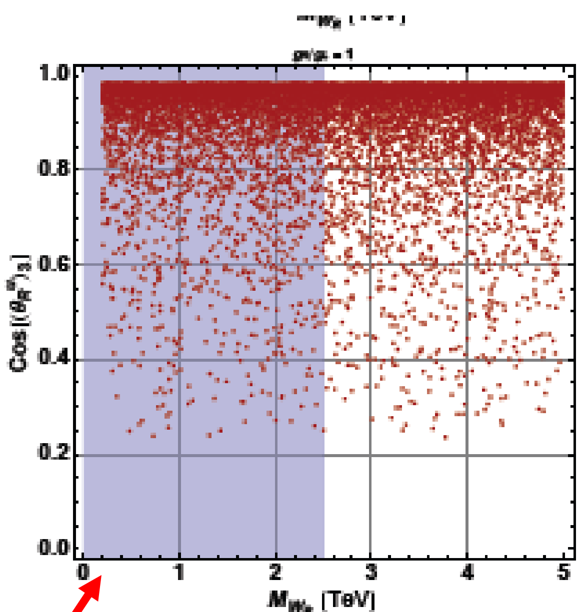


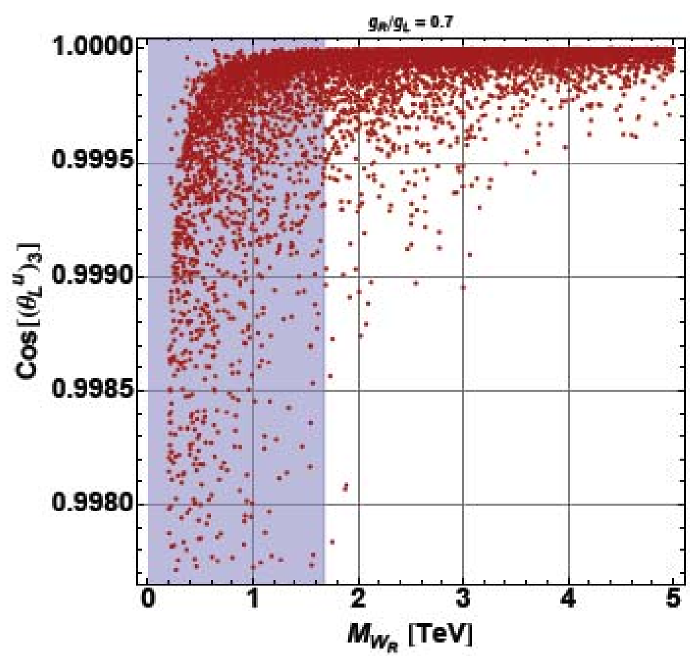


- TeV parity(blue): MH>10 TeV; MF>5 TeV; otherwise much lower-both near a TeV.

Special top sector

- Predicts large top mixings with vector like quarks due lower Y_t → **large FCNC** (in progress)





- **RH top** **LH top**

Consequences

- Reduction of top width
- $t \to cg$ probe $L_{eff} = \kappa \bar{t}_R \sigma^{\mu\nu} c_L G_{\mu\nu}$

SM prediction $\kappa \sim 10^{-5} (TeV)^{-1}$ D0: <.018 $(TeV)^{-1}$

Our model: intermediate top partner mediated graph

$$\to \quad \kappa \approx 10^{-3} \left(\frac{TeV}{Y_{u,33}} \right)^3 (TeV)^{-1}$$

- $\bar{B} \to X_s + \gamma$ probe: (Buras, Merlo, Stamou,arXiv:1105.5146)

Consequences

- **Non-unitarity of CKM matrix**

(Branco, Lavoura'86; Branco, Morozumi, Parada, Rebelo'94)

$$V_{CKM} \cong (1 - \frac{1}{2}\rho\rho^T)U \qquad \rho_L = \frac{\lambda v_L}{M_{\psi_{ui}}}$$

- Effects small; < 1-2 %
- **Collider constraints and prospects:**

(Aguilar-Saavedra)

LHC $pp \to \psi_t \overline{\psi}_t + X$, $\sigma \sim 10\ fb$ for 1 TeV mass

$\psi_t \to t + H \to bWb\overline{b}$

- Striking LHC signal 6b+2W

Solution to strong CP problem:

- Seesaw Quark mass matrix:

$$M_{q\psi} = \begin{pmatrix} 0 & \lambda_q v_L I \\ \lambda_q v_R I & <Y_q> \end{pmatrix}$$

- → Arg Det M = 0 at tree level. → $\theta_{tree} = 0$
- One loop also vanishes.
- No axion needed.

Planck scale corrections small for TeV scale parity unlike the axion solution.

(RNM, Senjanovic'78; Babu, RNM'89)

Neutrino sector

- Lepton sector similar

$$\langle\hat{Y}_e\rangle : \langle\hat{Y}_\mu\rangle : \langle\hat{Y}_\tau\rangle \;=\; m_e^{-1} : m_\mu^{-1} : m_\tau^{-1}$$

- Neutrinos Dirac in the minimal model:

$$M_{\nu-N} \;=\; \begin{pmatrix} 0 & \lambda_\nu v_L \\ \lambda_\nu v_R & \langle Y_\nu\rangle \end{pmatrix}$$

- For $\lambda_\nu \approx \lambda_e^{SM}$, correct nu masses emerge- much less tuning than SM.
- For Dirac nu, WR bound goes up to 3.3 TeV from BBN.
- Can be Majorana with susy.

Origin of flavor hierarchies

- → :<Y$_{U,D}$> encode the flavor pattern. How to understand this ?
- Step I: Higgs potential $V = V_U + V_D + V_{UD}$

$$V_U = -M_U^2 Tr Y_U^+ Y_U + \lambda_1 (Tr Y_U^+ Y_U)^2 + \lambda_2 Tr(Y_U^+ Y_U Y_U^+ Y_U)$$

- For $\lambda_2 < 0$, minimum of Vu is <Y_u>= (a, 0, 0); similarly for VD.
- Generates the largest flavon vev.

Next order and mixings

- **Two routes**

(i) Include effective d=6:

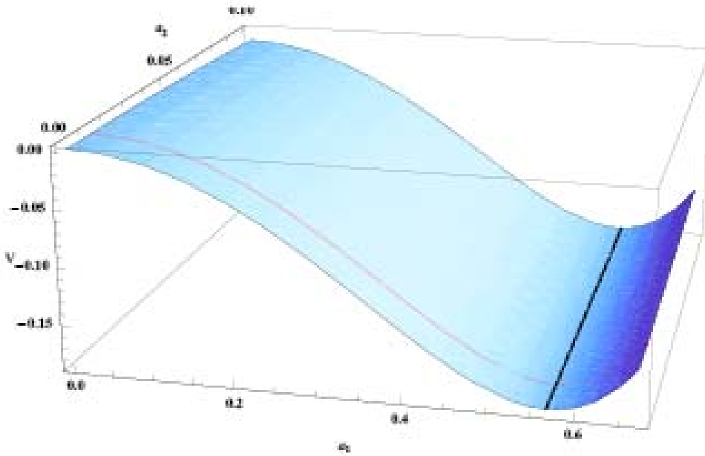
$$V = -m^2\,\mathrm{Tr}\left(Y_u^\dagger Y_u\right) + \lambda_1\left(\mathrm{Tr}\left(Y_u^\dagger Y_u\right)\right)^2 + \lambda_2 \mathrm{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u\right) + \lambda_3 \mathrm{Tr}\left(\left(Y_u^\dagger Y_u\right)\right)^3 + \lambda_4\,\mathrm{Det} Y_u$$
$$-m^2\,\mathrm{Tr}\left(Y_d^\dagger Y_d\right) + \lambda_1\left(\mathrm{Tr}\left(Y_d^\dagger Y_d\right)\right)^2 + \lambda_2 \mathrm{Tr}\left(Y_d^\dagger Y_d Y_d^\dagger Y_d\right) + \lambda_3 \mathrm{Tr}\left(\left(Y_d^\dagger Y_d\right)\right)^3 + \lambda_4\,\mathrm{Det} Y_d$$
$$+\lambda_5 \varepsilon_{ijk}\varepsilon^{abc} Y_{d\,a}^{\ i} Y_{u\,j}^{\ b} Y_{u\,k}^{\ c}$$

- With higher order terms + determinant term can generate all other terms- with hierarchy- e.g.

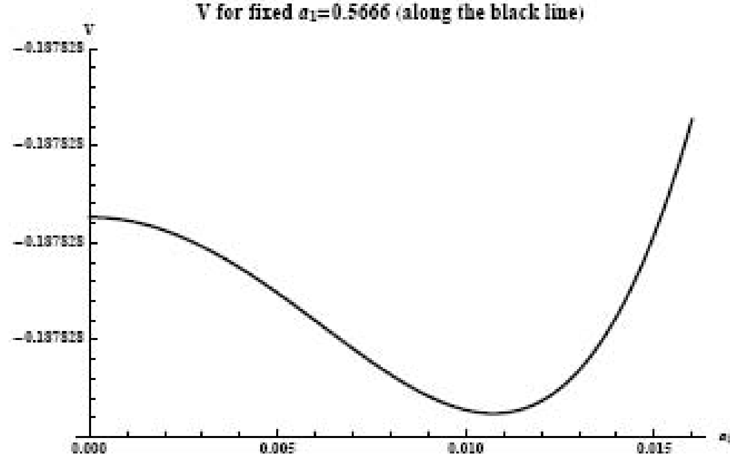
$$\langle Y_u \rangle = \begin{pmatrix} 0.5665 & 0.006906 & 0.001050 \\ 0.006906 & 0.01078 & 0.00002597 \\ 0.001050 & 0.00002597 & 0.0007688 \end{pmatrix}, \quad \langle Y_d \rangle = \begin{pmatrix} 0.5666 & 0 & 0 \\ 0 & 0.01070 & 0 \\ 0 & 0 & 0.0008006 \end{pmatrix}$$

A Numerical analysis

- Minimum of the potential:


(a)

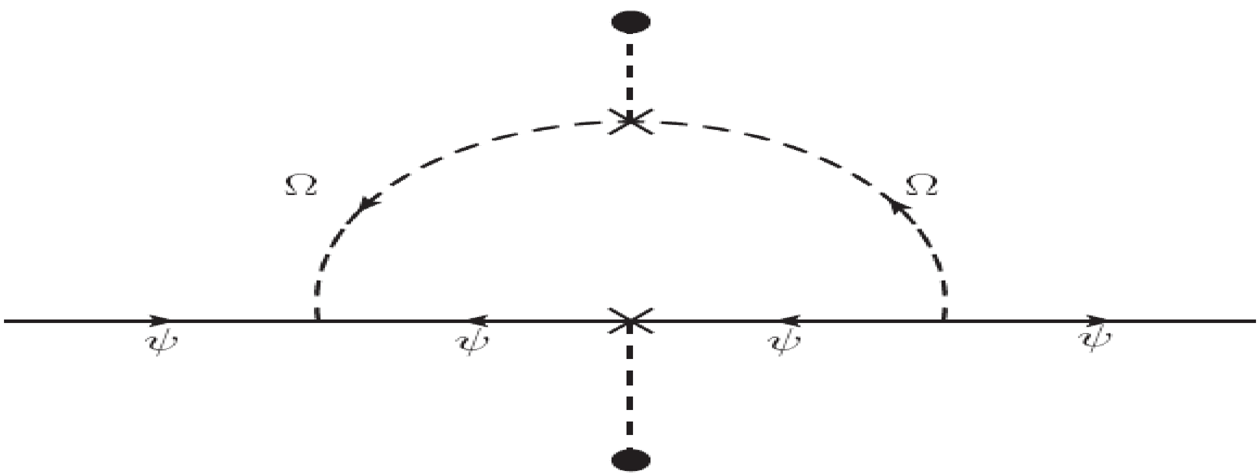
V for fixed a_1=0.5666 (along the black line)


(b)

Loop alternative

- **(ii) Loop alternative**: Add new interaction of vectorlike quarks: an example sextet

- $$L_I = \psi_u \psi_u \Omega_{L+R} + \Omega^{+}{}_L \Omega_R Y'$$



A SUSY version and R-parity

- Supersymmetrization allows only specific R-P violating terms:
- Forbids QLDc type terms. So no proton decay
- Allows $U^c D^c D^c$ and LLE^c terms

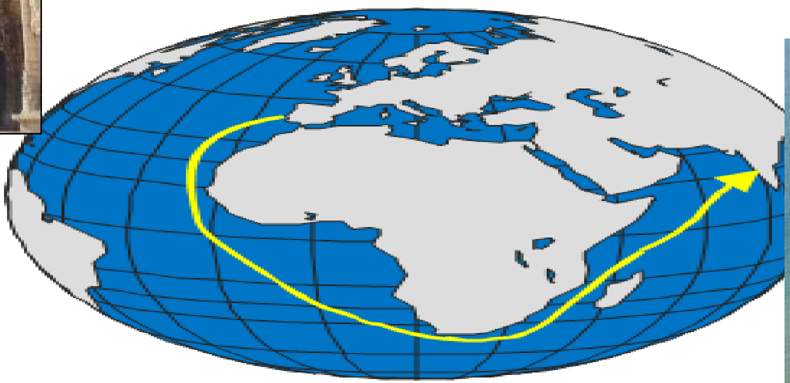
  (U,D,E are the vectorlike fermions)
- Through mixings with light quarks, they lead to neutron-anti-neutron oscillation (B=2 violation) with observable strength.
- LLE^c terms lead to Majorana mass for neutrinos with eV sterile neutrinos.

Conclusion

- New approach to gauged flavor FCNC allows flavor scale in TeV range (unlike simple gauged case);
- Key input: quark seesaw with new TeV mass vector-like fermions.
- LR version “protects all fermion masses”, solves strong CP problem and gives neutrino masses.
- Flavor mixings and hierarchies as a consequence of flavor breaking- May be computatble.
- Vectorlike quarks (and gauged flavor sym) may be observable at LHC !!

Thank you !

Lisbon,1497



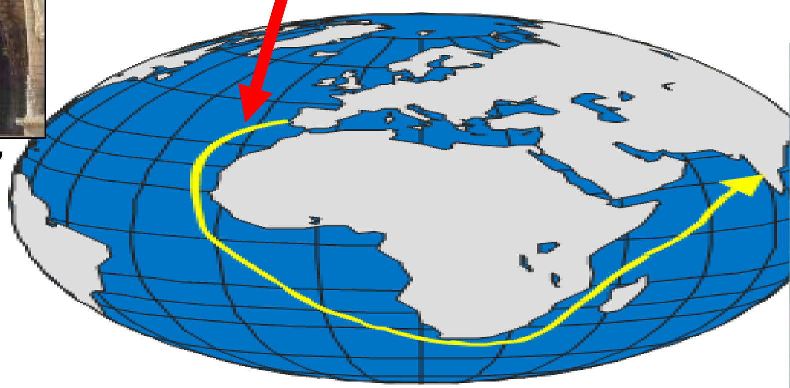
Vasco da Gama's route to Africa in 1497/98

Goa, India

Thank you !

Lisbon,1497

In flavor physics now, we may be here !



Vasco da Gama's route to Africa in 1497/98

Goa, India