Solving Strong CP without Axions and New TeV Physics

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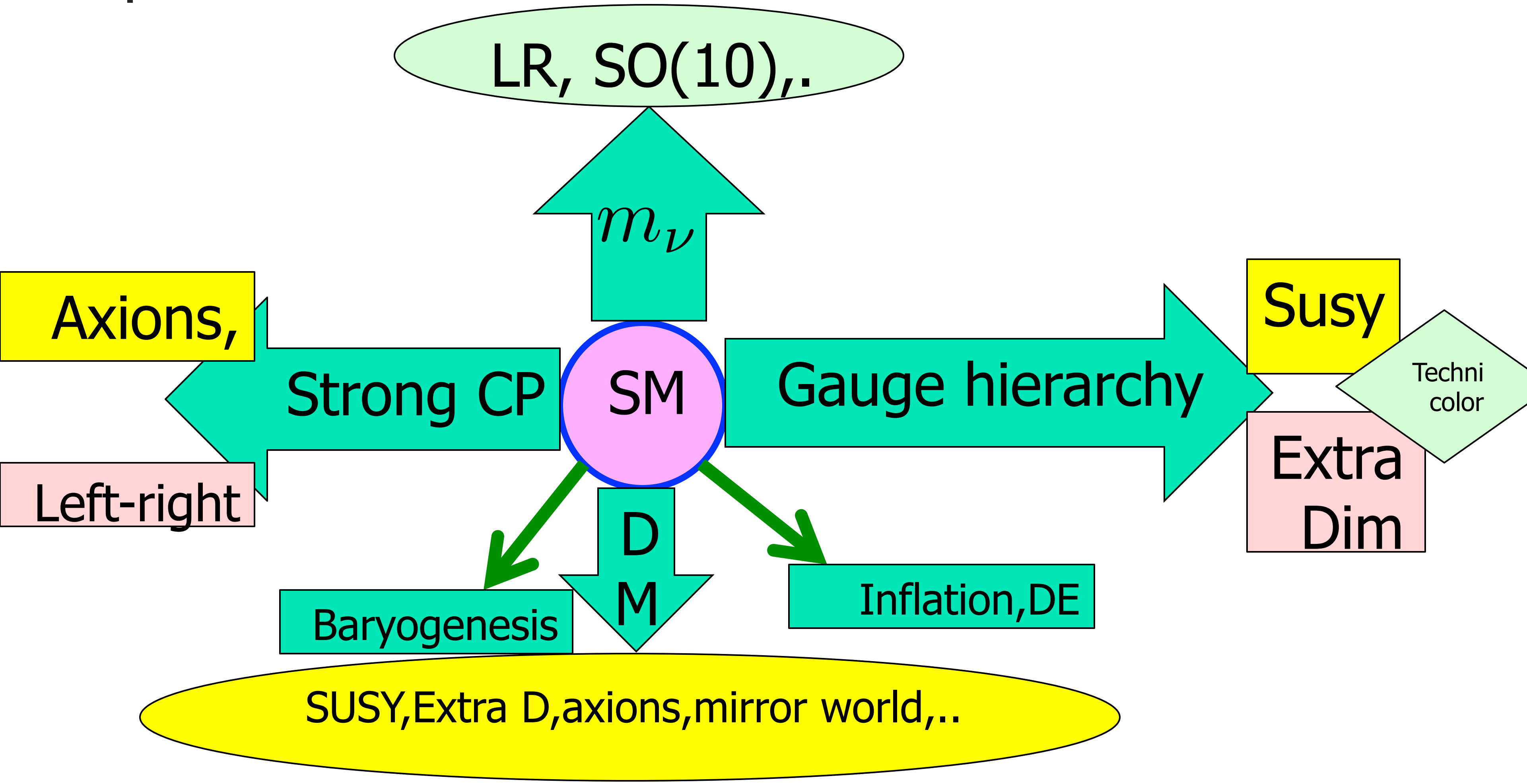
BSM Particle physics landscape



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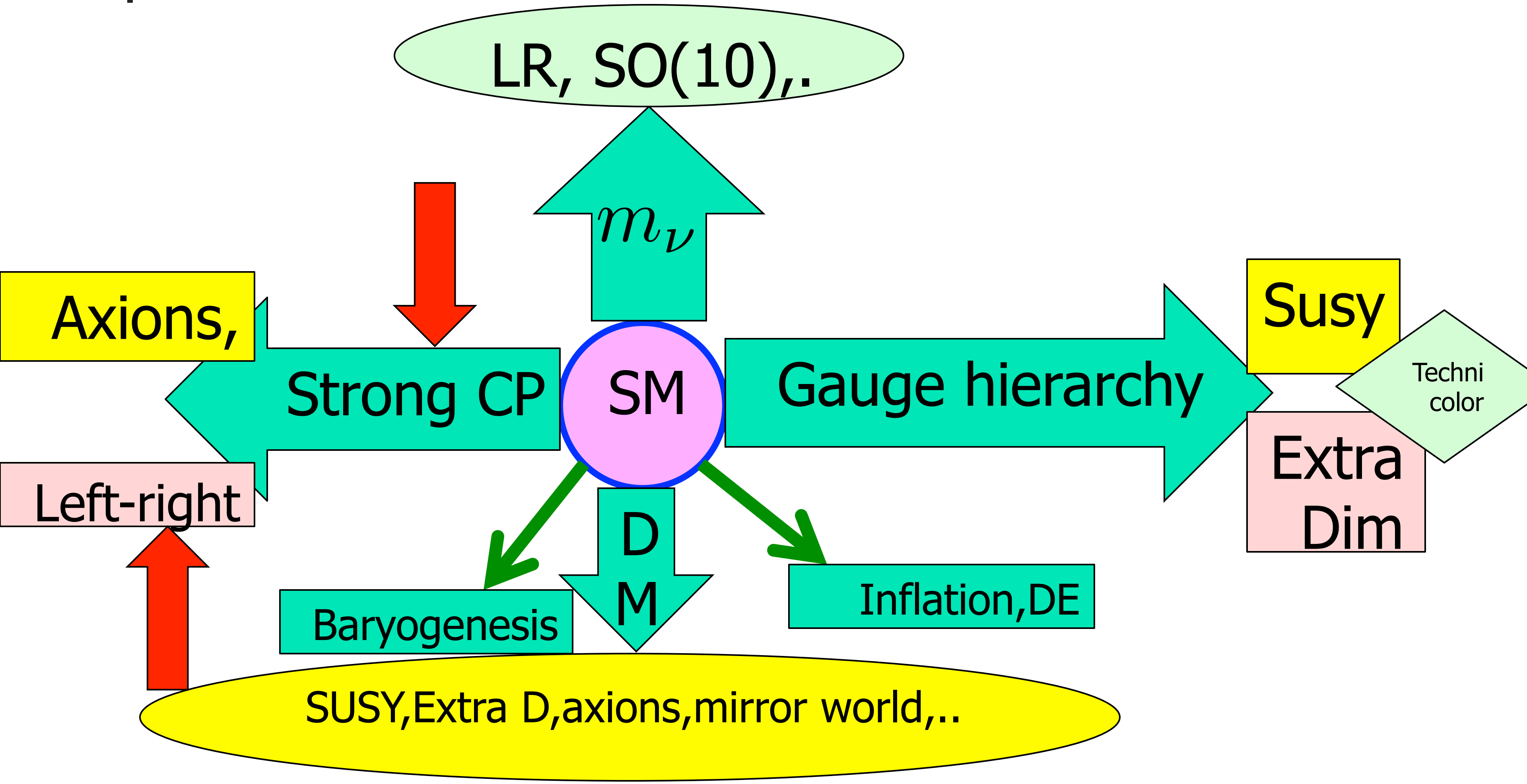


Strong CP: why $\theta_{QCD} \leq 10^{-10}$

- Popular solution: PQ → axion; no axion found yet
- Viable axion→PQ scale $f_a < 10^{12}$ GeV; $> 10^{10}$ GeV
- However, Planck scale corrections destabilize this soln. (Holman et al; Barr, Seckel'92) prefer lower scale solution

$$\delta\theta_{Planck} \sim \frac{f_a^5}{M_{Pl}\Lambda_{QCD}^4} \geq 10^{30}$$

Alternative solutions to strong CP solution via parity

- If weak interaction theory is parity symmetric, $\theta_{QCD} G\tilde{G}$ not allowed;
- Parity implies $M_q = M_q^\dagger \rightarrow Arg\ Det\ M = 0$

$$\rightarrow \bar{\theta} = \theta_{QCD} + \theta_{flavor} = 0$$ (tree)

- Weak Int break parity→ $\delta\theta^{loop} \neq 0$
- If small, a solution to strong CP without axion:

(Beg, Tsao'78; Mohapatra, Senjanovic'78; Babu, Mohapatra'90)

Parity symmetric weak interactions

- Gauge group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ x $\mathcal{P}$

- Fermions

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

$$L = \frac{g}{2}[\vec{J}_L{}^{\mu} \cdot \vec{W}_{\mu L} + \vec{J}_R{}^{\mu} \cdot \vec{W}_{\mu R}]$$

- Parity a spontaneously broken symmetry: $M_{W_R} \gg M_{W_L}$

Higgs sector and getting standard model

- Two Higgs doublets:
- Left doublet: $\chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}$ (SM Higgs)
- Right doublet: $\chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}$ (new)
- Sym breaking: $< \chi_R^0 >= v_R; < \chi_L^0 >= v_L$
- How to get fermion masses ?

Generalized seesaw

- Add singlet vector like quarks, leptons (P, N, E) $\equiv \psi$

$$\mathcal{L}_Y = Y_d \bar{Q}_L \chi_L N_R + Y_t \bar{Q}_L \tilde{\chi}_L P_R + Y_l \bar{L} \chi_L E_R + (L \to R) + h.c.$$

- Sym breaking→ doublet-singlet quark mass

$$M_{q\psi} = \begin{pmatrix} 0 & m_{q_L\psi} \\ m_{q_R\psi} & M_{\psi\psi} \end{pmatrix} \qquad m_{u,d} \sim \frac{m_{q_L\psi} m_{q_R\psi}}{M_{\psi\psi}}$$

(Berezhiani'84; A. Davidson, Wali'87;Babu, RNM'89)

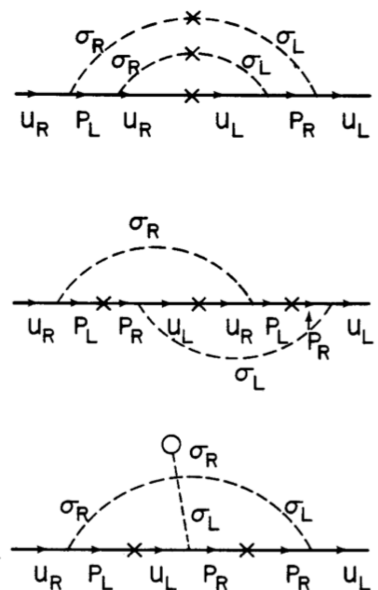
- Top partner light;

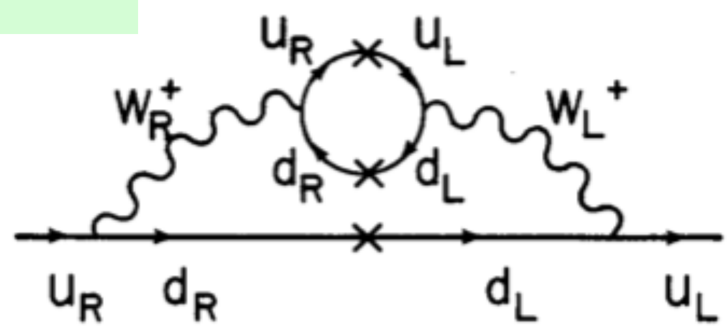
Solving Strong CP without axion

- Quark mass matrix: $M_{q\psi} = \begin{pmatrix} 0 & m_{q_L\psi} \\ m_{q_R\psi} & M_{\psi\psi} \end{pmatrix}$
- Parity→ $m_{q_L,\psi} = m^{\dagger}_{q_R,\psi}$ →Arg Det M = 0 (tree) →

$$\theta_{tree} = 0$$

- 2-loop estimate of θ





$$\bar{\theta} \sim \frac{g^4 m_b m_t}{(16\pi^2)^2 v_R^2} \sim 10^{-10}$$

(Babu, RNM'89)

Planck scale corrections and upper limit on scales

- Planck scale corrections: $\frac{\bar{Q}_L \chi_L \chi_R^\dagger Q_R}{M_{Pl}}$

$$\frac{v_L v_R}{M_{Pl}}$$

$$M_{q\psi} = \begin{pmatrix} 0 & m_{q_L\psi} \\ m_{q_R\psi} & M_{\psi\psi} \end{pmatrix}$$

- Arg Det M not zero and < 10^{-10} →

$$\rightarrow v_R \leq 100\ TeV$$

Summary of the model

- Gauge group: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Fermions:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \Leftrightarrow \begin{pmatrix} u_R \\ d_R \end{pmatrix} \qquad (P, N, E, \mathcal{N})_{L,R}$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \Leftrightarrow \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- Higgs fields:

$$\begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix} \quad \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}$$

New TeV Mass Fields:

- Heavy Higgs: H
- Vector-like fermions: (P, N, E)
- New vector bosons: W_R , Z'
- Right handed and singlet neutrinos $(\nu_R, \mathcal{N}_L, \mathcal{N}_R)$

- Masses, decays,… for phenomenology

Two parts to rest of the talk

Part I: Implications for Higgs and new TeV scale physics:

Part II: From universal seesaw to Gauged Flavor

Implications for Higgs Boson

- Only one extra neutral Higgs boson; (Y. Zhang, R. N. M'14)
- Higgs potential:

$$V = -\mu_L^2 \chi_L^\dagger \chi_L - \mu_R^2 \chi_R^\dagger \chi_R , \\ +\lambda_1 \left[(\chi_L^\dagger \chi_L)^2 + (\chi_R^\dagger \chi_R)^2 \right] + \lambda_2 (\chi_L^\dagger \chi_L)(\chi_R^\dagger \chi_R)$$

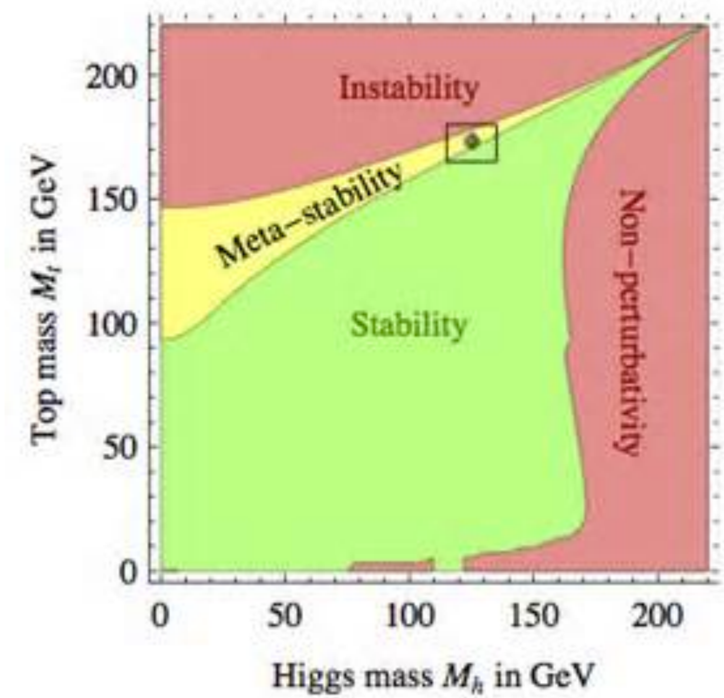
- Positivity→ $\lambda_1 > 0; 2\lambda_1 + \lambda_2 > 0$
- Higgs masses:

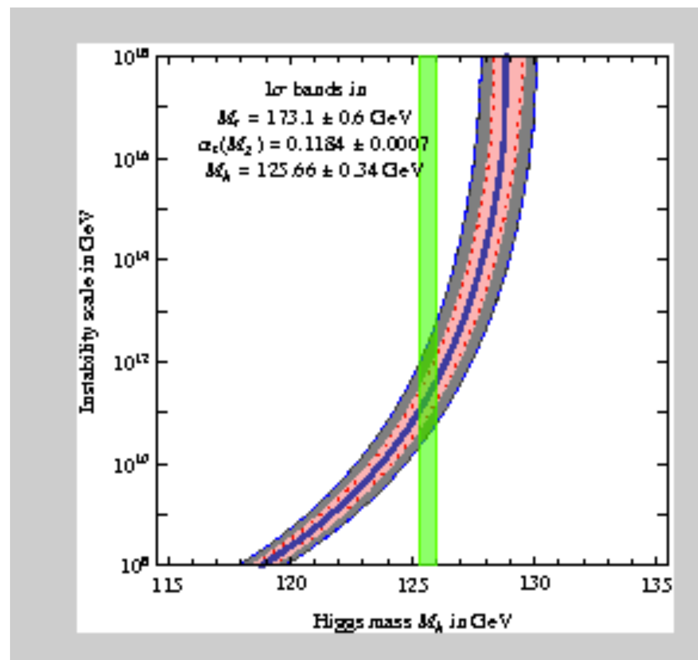
$$M_h^2 = 2\lambda_1 \left(1 - \frac{\lambda_2^2}{4\lambda_1^2} \right) v_L^2$$

$$M_H^2 = 2\lambda_1 v_R^2 .$$

Vacuum stability issue

- Standard model: m_h =125 GeV→ λ near critical
- Turns negative around 10^{10} GeV; making vacuum unstable !! (Cabibbo,Maiani,Parisi,Petronzio; Lindner,….)





Is this a serious problem ?

- The time it takes to tunnel to the false vacuum is $\tau_{vac} > \tau_U$; We are safe but at risk !!

- Many people have taken this as an indication that there is new physics at the TeV scale (or at least below 10^{10} GeV).

- What does our strong CP model say about this ?

Vacuum stability in Quark seesaw model

- Note: $$M_h^2 = 2\lambda_1 \left(1 - \frac{\lambda_2^2}{4\lambda_1^2}\right) v_L^2$$

- λ_1 Can be larger; running depends on v_R, M_ψ

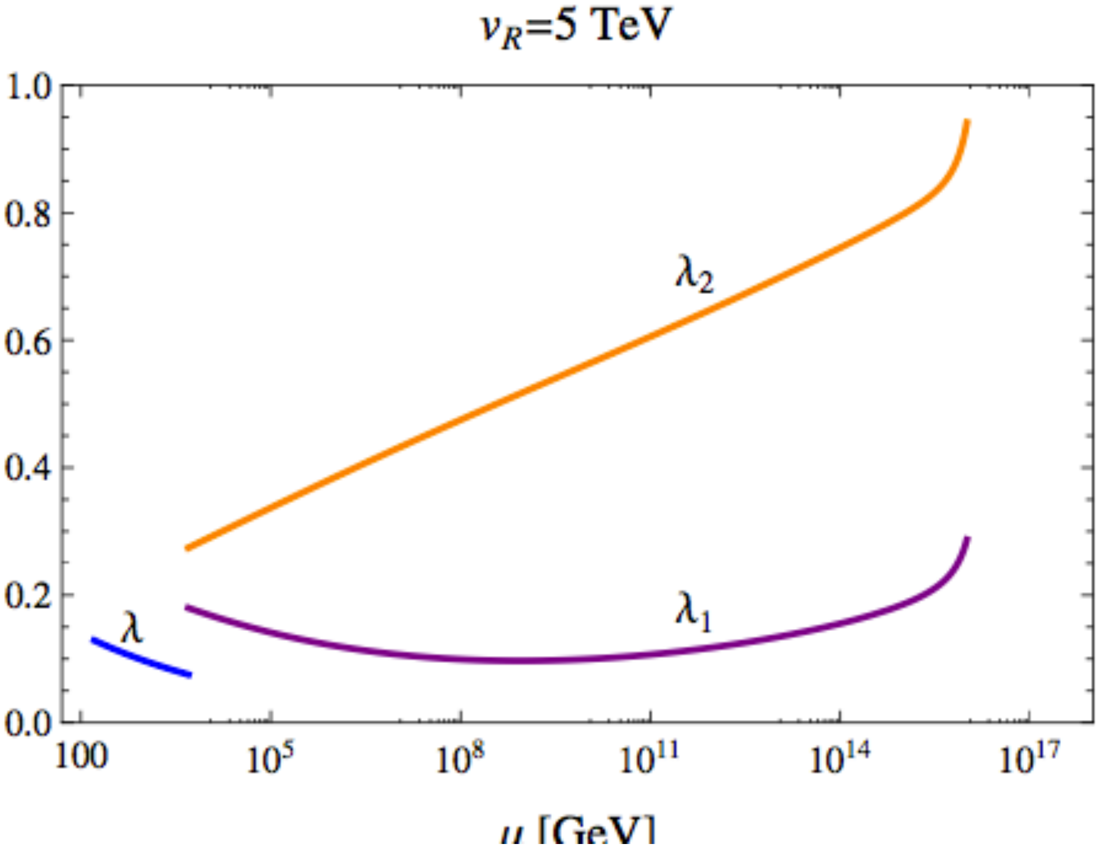
- Choose: $M_{P_3} = M_{N_3} = M_{E_3}$, $M_\psi = v_R$

- Above v_R, RGEs change;

RGE for λ_1 and λ_2

- .

$\lambda_2 > 0$



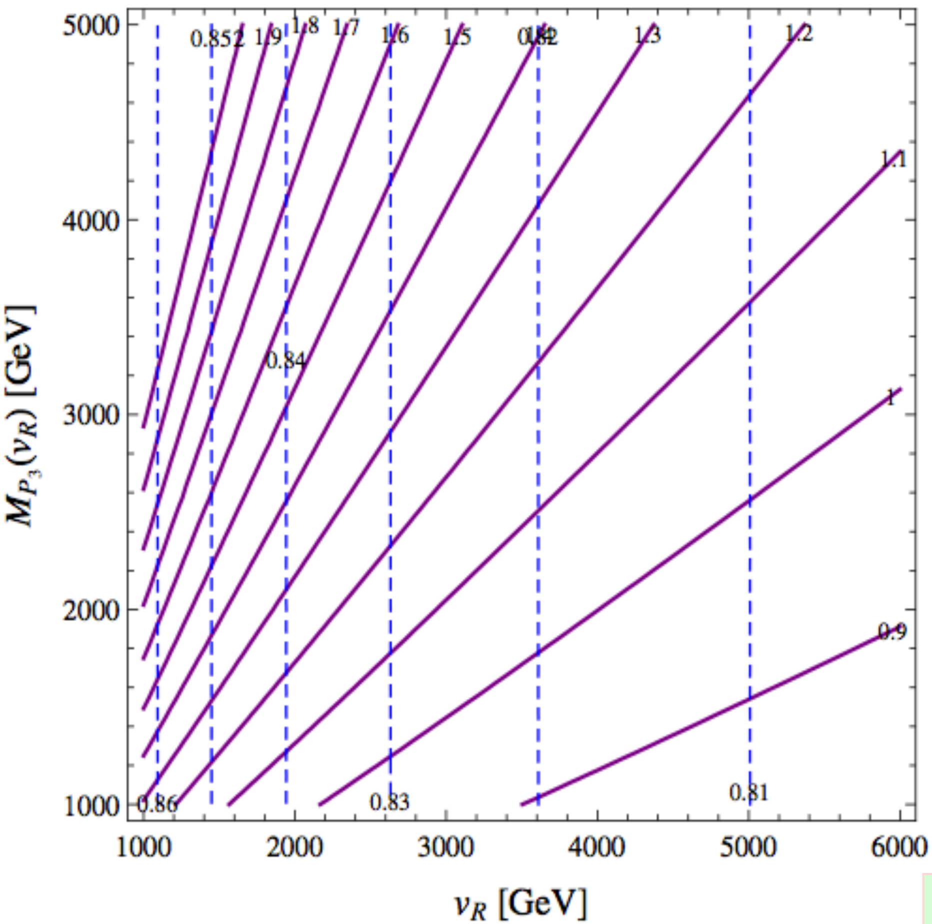
- Vacuum stability problem solved (Yongchao Zhang, RNM'14)

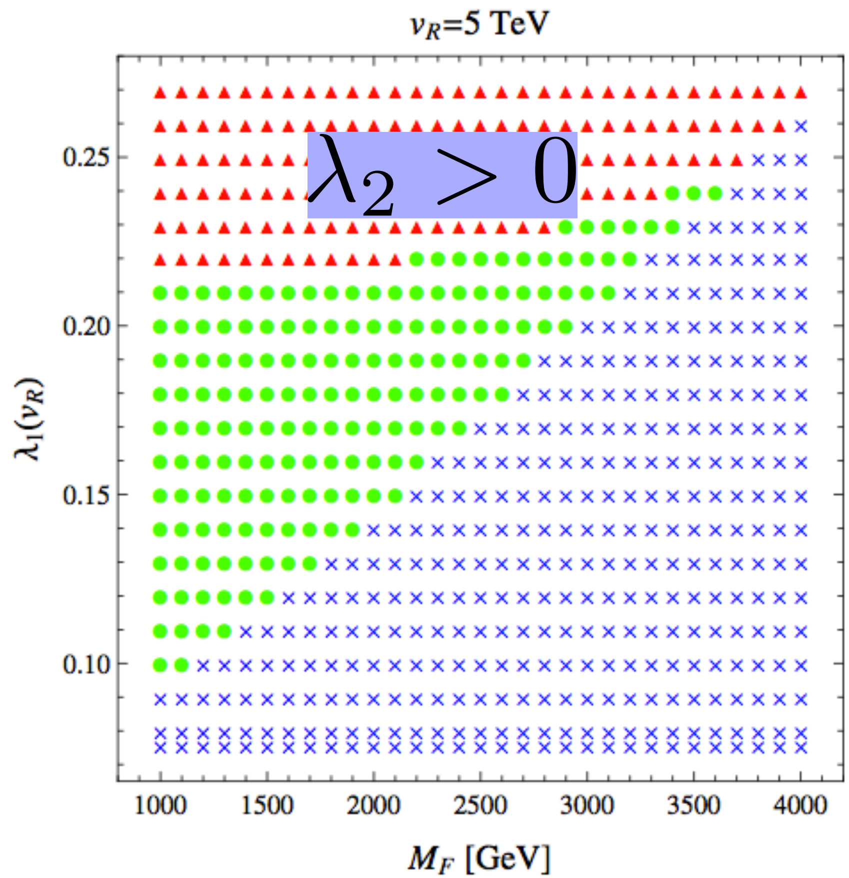
Constraints of perturbativity and vacuum stability

- How large can λ_1 and λ_2 be ?
- If we demand perturbativity till GUT scale, λ_1 cannot be too large !!
- Depends on the 3rd gen new fermions masses since they determine Yukawas that go into running.

- Heavy Higgs mass bounds: $0.4 \leq \frac{M_H}{v_R} \leq .7$

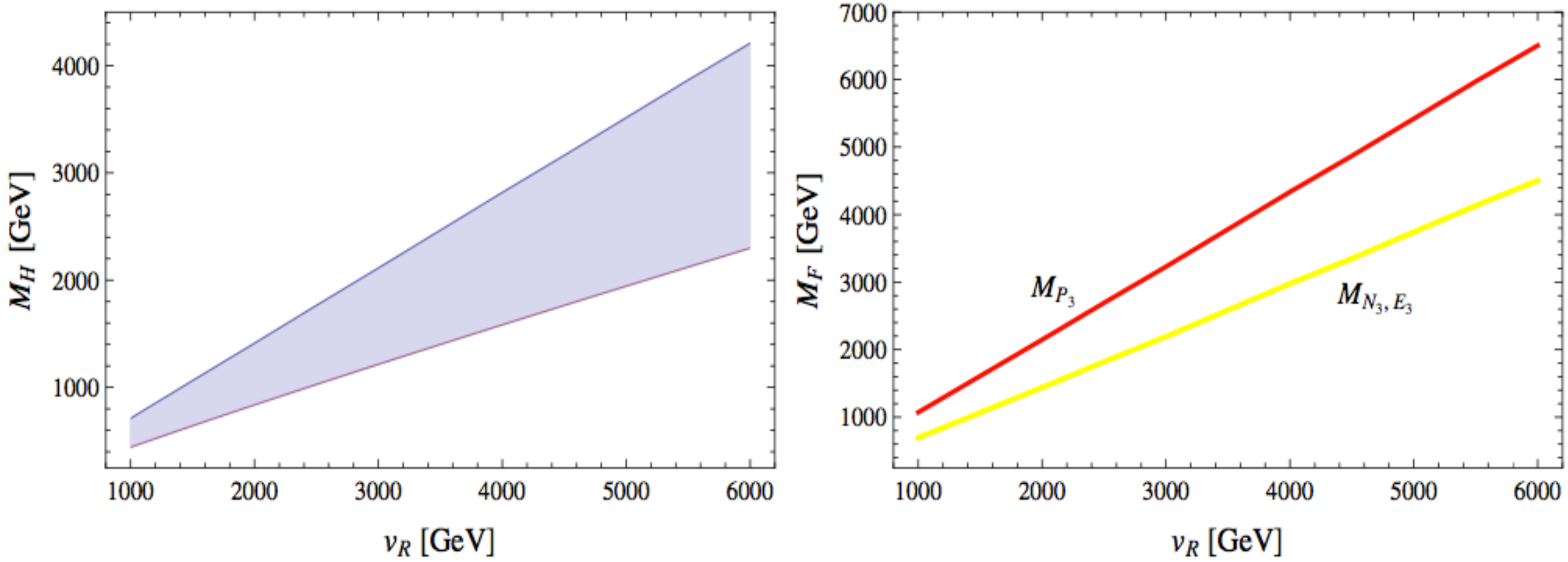
Results





$$M_{P_3,N_3,E_3} \leq v_R$$

Detailed Mass Bounds:

- 

$$\lambda_2 > 0$$

- $\lambda_2 < 0$ limits stronger on masses of N_3
- LHC search info only below TeV.

Heavy Higgs decays

- Mass: v_R > 5 TeV (CMS,ATLAS)→ M_H > 2 TeV;
- Dominant decays: (enhanced by v_R)

$$H \to hh\,, WW, ZZ$$

- For large Higgs (H) mass, $W_{\text{longitudinal}}$, Z_{Long}

$$\Gamma_{hh} : \Gamma_{WW} : \Gamma_{ZZ} = 1 : 2 : 1$$

- Possible hh channel signal:

$$H \to hh \to b\bar{b}\gamma\gamma$$

- Characteristic of left-right with doublet breaking

Other phenomenology

- hhh couplings unchanged;
- hbb couplings changes by ~1% for low v_R

Quark seesaw and Top partner at LHC

- New vector-like quarks: current constraints allow TeV top partner and large mixing with t:

$$pp \to t' + \bar{t}' \qquad t' \to t + h$$

$$t \to b + \ell + \bar{\nu}; h \to b + \bar{b}$$

$$pp \to 6b + \ldots$$

- ATLAS search: this mode: M_T > 640 GeV; M_B > 590 GeV (same sign dilepton)

Quark seesaw and Top partner at LHC

- New FCNC effects $t \to c + g, c + Z, c + \gamma$

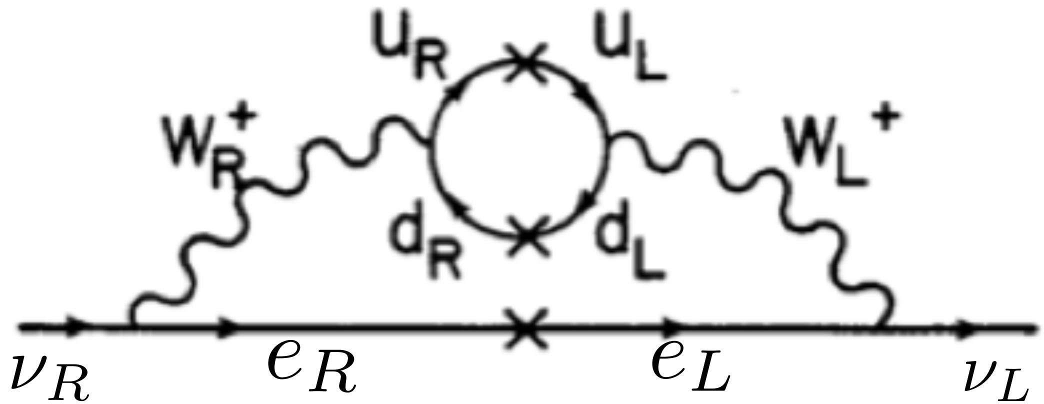
$$\mathcal{L}_I = \kappa_g \bar{t} \sigma_{\mu\nu} c G^{\mu\nu}$$

$$\kappa_g \leq 10^{-3}\ TeV^{-1} \quad SM \to 10^{-5}\ TeV^{-1}$$

- Current limits: ATLAS: $\kappa_{tcg} \leq 1.1 \times 10^{-2}\ TeV^{-1}$

Neutrino masses

- . Dirac alternative: no singlet neutral fermion $\mathcal{N}$
- Neutrino mass at two loop: Dirac nu: (D. Chang, RNM'87)



- Not the preferred solution since to avoid SN1987A constraints, need extra singlet scalars

Generalized seesaw for nu's

- Add singlet neutral fermion $\mathcal{N}$
- Two alternatives: Dirac or Majorana:

$$(\nu_L, \nu_R, \mathcal{N}_L, \mathcal{N}_R)$$

$$\begin{pmatrix} 0 & 0 & 0 & \frac{1}{\sqrt{2}} Y v_L \\ 0 & M_L & \frac{1}{\sqrt{2}} Y v_R & M_N \\ 0 & \frac{1}{\sqrt{2}} Y^T v_R & 0 & 0 \\ \frac{1}{\sqrt{2}} Y^T v_L & M_N & 0 & M_R \end{pmatrix}$$

- $M_{L,R}=0 \rightarrow$ Dirac; otherwise, Majorana.

Majorana Alternative:

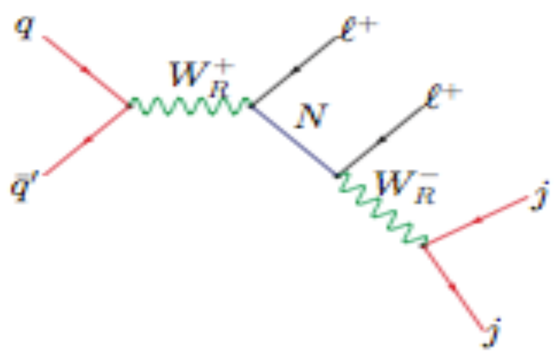
- Dirac masses for left and Right $\mathcal{N}$ are same.
- For 10 TeV $\mathcal{N}$ Dirac masses, we need left and right Majorana masses $M_{L,R}$ to be different !!

$$\mathcal{M}_\nu \simeq -\frac{1}{2} v_L^2 Y \left(M_R - M_N^T M_L^{-1} M_N\right)^{-1} Y^T$$

- An example that works: $M_R = 10^{10}$ GeV; $M_L \sim$ TeV
- Otherwise, 3 eV steriles and against BBN, WMAP , Planck etc.
- TeV RH Majorana neutrinos as in LR models.

Searching for WR for Majorana nu

- Live WR production: $u\bar{d} \to W_R \to l^+ N$
- Subsequent N-decay via (a) νN mixing and/or (b) W_R exchange
- Generic type I $\theta_{\nu N} << 10^{-3}, M_{W_R} < 4TeV$ (a) negligible;
- Dominant graph(b)



$$N \to l^\pm jj$$

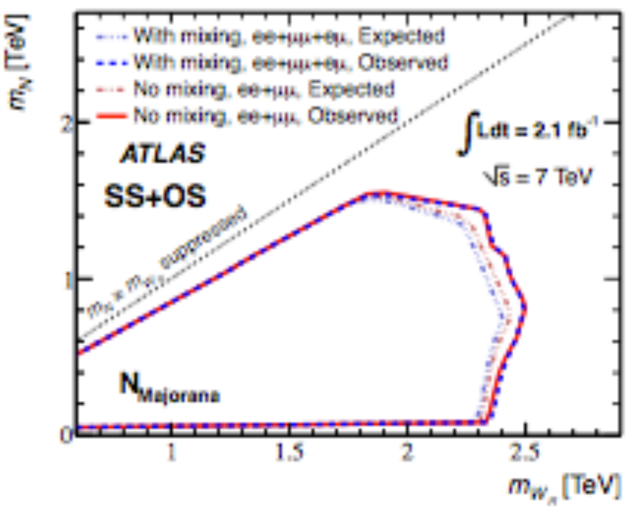
(RR diagram)

(Keung, Senjanovic'82)

- **Golden channel:** $\ell^\pm \ell^\pm jj$ Generic LR seesaw

Current LHC analysis: only W_R graph but not large $V_{\ell N}$

- Current W_R limits from CMS, ATLAS 2.5-2.9 TeV;



- 14-TeV LHC reach for M_{WR} 6 TeV with 300 fb^{-1}

Understanding Flavor using universal seesaw

- Generic universal seesaw→ $$M_{q\psi} = \begin{pmatrix} 0 & m_{q_L\psi} \\ m_{q_R\psi} & M_{\psi\psi} \end{pmatrix}$$
- Flavor originates from combination of $$m_{q\psi},\ M_{\psi\psi}$$
- Interesting possibility: if $m_{q\psi} = m_0\mathbf{1}$; then, all flavor arises from higher scale physics of the vector-like fermions;
- Universal seesaw allows flavor gauging that leads to this possibility naturally !!

Beyond Universal Seesaw to Gauged Flavor

- Guadagnoli, Mohapatra , Sung, arXiv: 1103.4170 JHEP 04, 093 (2011)
- SM+0 Yuakawas→ G_f $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e \times U(3)_N$
- With vector-like fermions+LR→ Gauged flavor group
- $G_f = \boxed{U(3)_{Q,L} \times U(3)_{Q,R} \times U(3)_{\ell,L} \times U(3)_{\ell,R}}$

➡ $Y_{u,d,l}=1$;All flavor originates from G_f breaking

- Minimizing the potential for G_f Higgs→flavor

Details of Model:

- Anomaly free Fermion and Higgs assignment: *$\mathcal{N}$ needed*

	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	$SU(3)_{Q_L}$	$SU(3)_{Q_R}$	$SU(3)_c$	$SU(3)_{\ell_L}$	$SU(3)_{\ell_R}$
Q_L	2		$\frac{1}{3}$	3		3		
Q_R		2	$\frac{1}{3}$		3	3		
ψ_L^u			$\frac{4}{3}$		3	3		
ψ_R^u			$\frac{4}{3}$	3		3		
ψ_L^d			$-\frac{2}{3}$		3	3		
ψ_R^d			$-\frac{2}{3}$	3		3		
L_L	2		-1				3	
L_R		2	-1					3
ψ_L^e			-2					3
ψ_R^e			-2				3	
ψ_L^ν			0					3
ψ_R^ν			0				3	
χ_L	2		1					
χ_R		2	1					
Y_u				$\bar{3}$	3			
Y_d				$\bar{3}$	3			
Y_ℓ							$\bar{3}$	3
Y_ν							$\bar{3}$	3

Some details:

- Higgs fields:Flavon fields: $Y^H_{u,d}(3,\bar{3})$ (EW singlets)
- Flavor from sym br. $Y_{u,d,\ell} = \mathbf{1}$

$$\mathcal{L}_Y = Y_d \bar{Q}_L \chi_L N_R + Y_t \bar{Q}_L \tilde{\chi}_L P_R + Y_l \bar{L} \chi_L E_R + (L \to R) + h.c.$$

$$+\lambda_1 \bar{P}_L Y^H_u P_R + \lambda_2 \bar{N}_L Y^H_d N_R + \lambda_\ell \bar{E}_L Y^H_\ell E_R + \ldots$$

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

$$m_d = \frac{v_L v_R}{< Y^H_d >} \qquad m_u = \frac{v_L v_R}{< Y^H_u >}$$

Strategy for flavor

- Potential for Y's: $V(Y_u^H, Y_d^H)$
- Minimize: $\dfrac{\partial V(Y_u^H, Y_d^H)}{\partial Y} = 0$
- Minimum gives flavor pattern:
- Will lead to different results from MFV case:
  (Alonso, Gavela, Merlo, Rigolin'11)

MFV case and essential nature of EW gauge group

- MFV case: $G_f = SU(3)_Q \times SU(3)_u \times SU(3)_d$

  $Y_u = (3, 3^*, 1)$;

  $Y_d = (3, 1, 3^*)$

- Invariants: $Tr(Y_u^\dagger Y_u), Tr(Y_d^\dagger Y_d); Det(Y_u), Det(Y_d),$

  disjoint ones→ $Tr(Y_u^\dagger Y_u Y_u^\dagger Y_u), Tr(Y_d^\dagger Y_d Y_d^\dagger Y_d)$

- Only mixed one: $Tr(Y_u Y_u^\dagger Y_d Y_d^\dagger)$
- Diagonalize $Y_{u;}$ Y_d if no mixed term and $V_{CKM} = 1$

(Gavela et al)

Situation different with LR

- G_f = SU(3)$_{QL}$ x SU(3)$_{QR}$: Y_u =(3,3*) =Y_d
- Allowed invariants in the potential:

$$Tr(Y_u^\dagger Y_u), Tr(Y_d^\dagger Y_d); Det(Y_u), Det(Y_d),$$

$$Tr(Y_u^\dagger Y_u Y_u^\dagger Y_u), Tr(Y_d^\dagger Y_d Y_d^\dagger Y_d)$$

- Many mixed ones: $\varepsilon\varepsilon(Y_u Y_u Y_d + Y_u Y_d Y_d)$

+ $\sum_{i,j,k,l=u,d} Tr(Y_i^\dagger Y_j Y_k^\dagger Y_l)$ +h.c.

$V_{CKM} \neq 1$ guaranteed !!

Susy version and RPV predictions

- The only gauge invariant RPV interactions come from: $W_{RPV} = P^c N^c N^c \ + \ P N N$
- No quark-lepton mixing terms due to gauged flavor ! So no proton decay problem !!
- Vectorlike quark mixings with light quarks→ $\Delta B = 1$ terms with couplings given by

Patterns of RPV:

- .

$\Delta B = 1$ operator	strength
$u^c s^c b^c$	$V_{ud}\, m_u\, m_s\, m_b / m_t^3$
$c^c s^c b^c$	$V_{us}\, m_c\, m_s\, m_b / m_t^3$
$t^c s^c b^c$	$V_{ub}\, m_t\, m_s\, m_b / m_t^3$
$u^c d^c b^c$	$V_{cd}\, m_u\, m_d\, m_b / m_t^3$
$c^c d^c b^c$	$V_{cs}\, m_c\, m_d\, m_b / m_t^3$
$t^c d^c b^c$	$V_{cb}\, m_t\, m_d\, m_b / m_t^3$
$u^c d^c s^c$	$V_{td}\, m_u\, m_d\, m_s / m_t^3$
$c^c d^c s^c$	$V_{ts}\, m_c\, m_d\, m_s / m_t^3$
$t^c d^c s^c$	$V_{tb}\, m_t\, m_d\, m_s / m_t^3$

(Franceschini, Mohapatra'13, JHEP; similar to MFV type results: Grossman et al.)

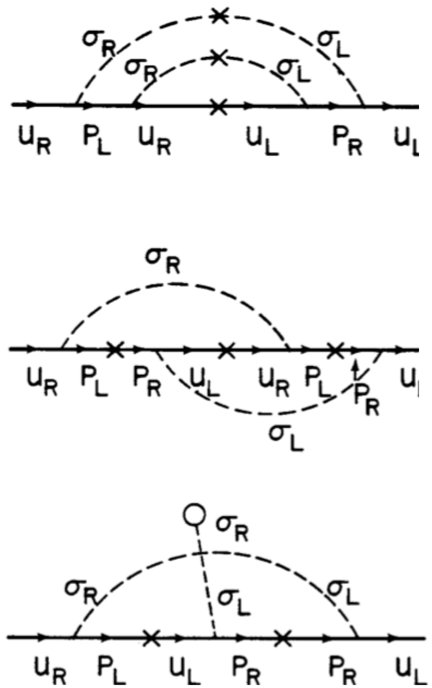
Summary:

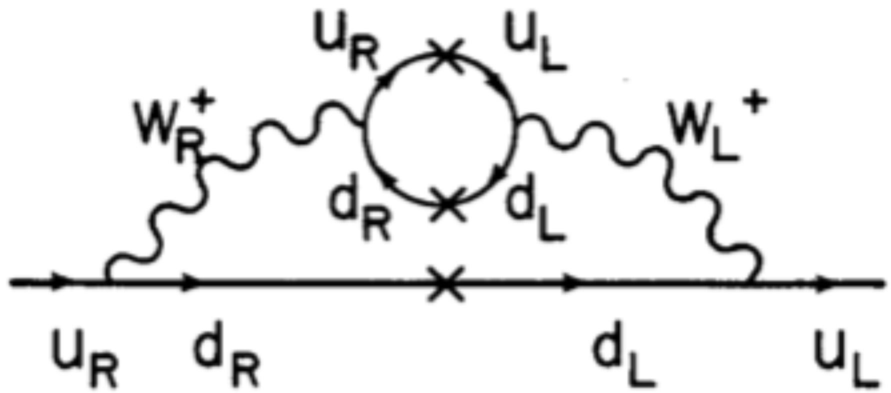
- Universal seesaw for quarks motivated by non-axion solution to strong CP; Protection from Planck effects Suggests next scale (LR) in the several TeV range;
- Simple Higgs sector (h, H); solves vacuum stability problem of SM;Bounds on heavy Higgs mass; LHC accessible; decay rate pattern testable model feature!
- Vectorlike heavy quarks in TeV range; Once TeV WR is observed, no evidence for t, b tau partners below WR mass will rule out this solution to strong CP !!
- Beyond Universal seesaw to Gauged flavor: a new approach to flavor.

Extra slides

Estimating θ

- 2-loop
  - (Babu, RNM'89)





$$\bar{\theta} \sim \frac{g^4 m_b m_t}{(16\pi^2)^2 v_R^2} \sim 10^{-10}$$

- **Universal seesaw solves both strong CP and neutrino mass problem !!**

Future Sensitivities

- **Experiment**

No.	Observable	Upper Limit	Future Sensitivity
1.	$B(\mu \to e\gamma)$	2.4×10^{-12} [1]	$1-2 \times 10^{-13}$ [6], 10^{-14} [6]
2.	$B(\mu \to eee)$	10^{-12} [2]	10^{-16} [8], 10^{-17} [7]
3.	$R_{\mu e}^{\mathrm{Ti}}$	4.3×10^{-12} [3],	$3-7 \times 10^{-17}$ [10, 9], 10^{-18} [11, 7]
4.	$R_{\mu e}^{\mathrm{Au}}$	7×10^{-13} [4]	$3-7 \times 10^{-17}$ [10, 9], 10^{-18} [11, 7]
5.	$B(\tau \to e\gamma)$	3.3×10^{-8} [5]	$1-2 \times 10^{-9}$ [13, 12]
6.	$B(\tau \to \mu\gamma)$	4.4×10^{-8} [5]	2×10^{-9} [13, 12]
7.	$B(\tau \to eee)$	2.7×10^{-8} [5]	2×10^{-10} [13, 12]
8.	$B(\tau \to e\mu\mu)$	2.7×10^{-8} [5]	10^{-10} [12]
9.	$B(\tau \to \mu\mu\mu)$	2.1×10^{-8} [5]	2×10^{-10} [13, 12]
10.	$B(\tau \to \mu ee)$	1.8×10^{-8} [5]	10^{-10} [12]

Table 1: Current upper limits and future sensitivities of CLFV observables under study.

CLFV that directly relates to neutrino Majorana mass

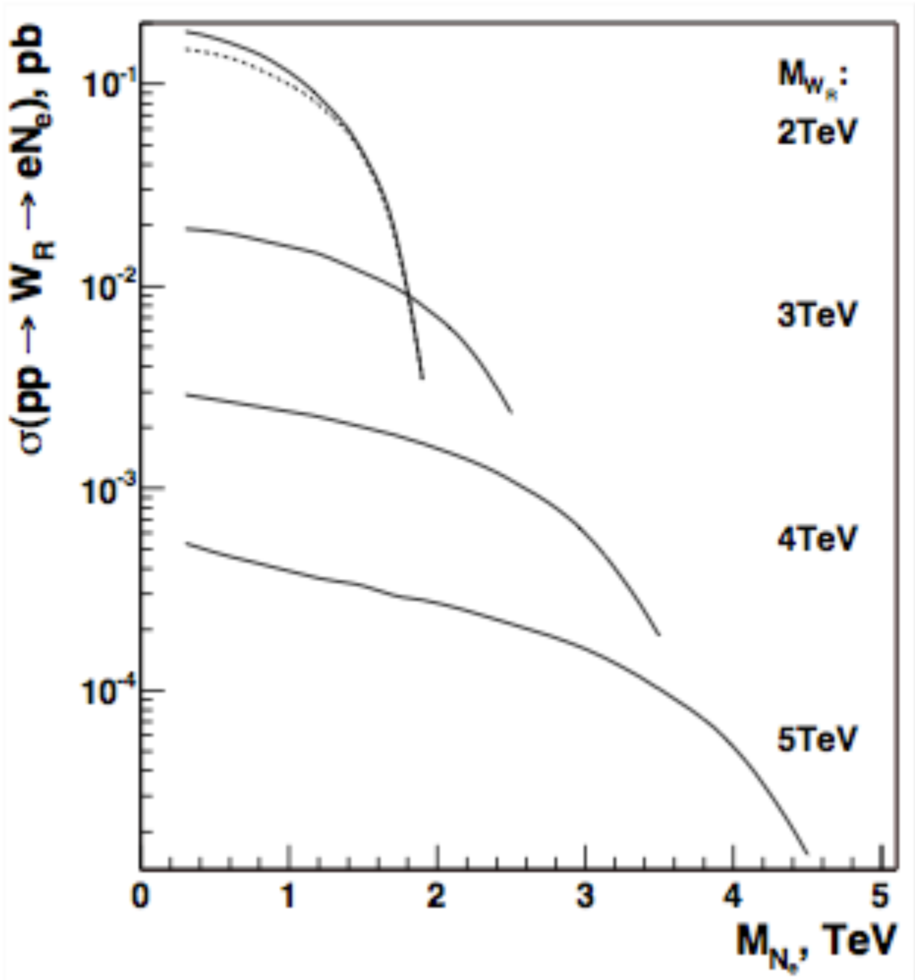
- $\mu \to e\gamma, \mu \to 3e, \mu^- \to e^-$ conserve L and are not true tests of Majorana nu mass.
- However $\mu^- \to e^+, \mu^- \to \mu^+$ are $\Delta L \neq 0$

$$B(\mu^- Ti \to e^+ Ca) \leq 3.6 \times 10^{-11}$$

- Flavor analog of $\beta\beta_{0\nu}$ decay
- Small in minimal type I
- Other related processes: $K^+ \to \pi^- e^+ e^+, \pi^- e^+ \mu^+$

WR production cross section at LHC

- Ginienko et al.



Beyond quark seesaw to Gauged Flavor

- New way to understand flavor:
- Quark seesaw allows anomaly free flavor gauging: (Grinstein, Redi, Villadoro'11; Guadagnoli'11, R. N. M., Sung'11)
- Gauge group: $G_{LR} \times SU(3)_{q_L} \times SU(3)_{q_R}$

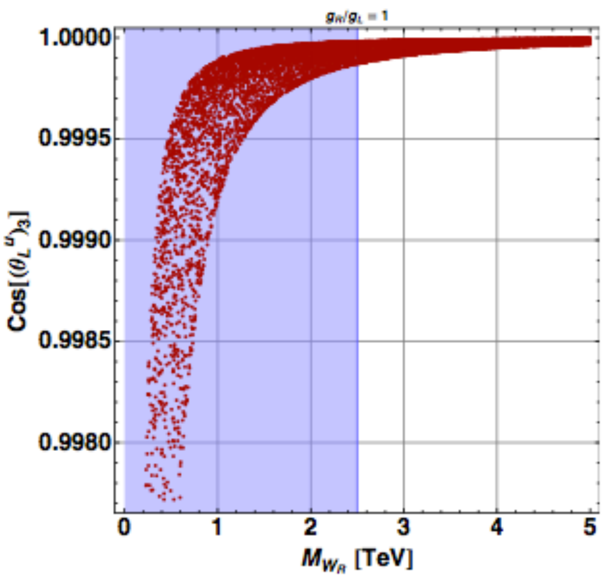
Quark seesaw matrix:

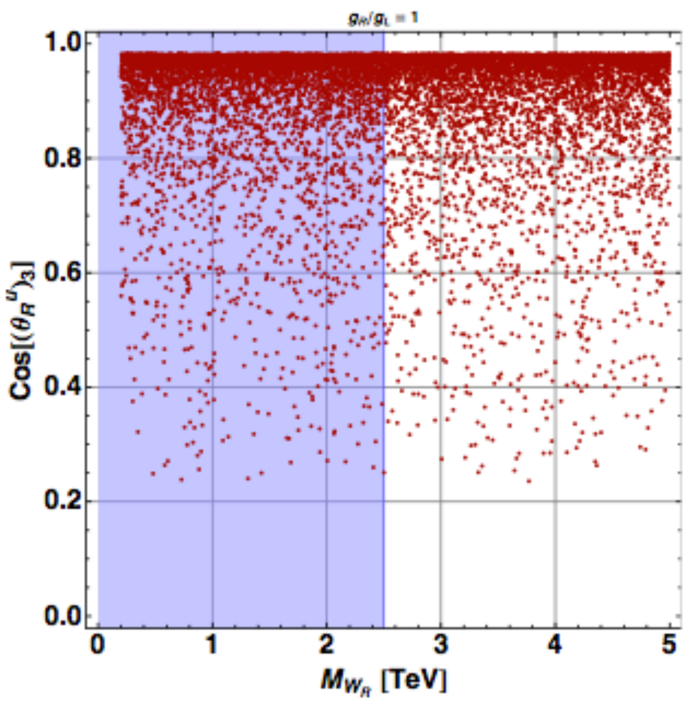
- $$\begin{pmatrix} 0 & \lambda_u v_L \\ \lambda_u v_R & < Y_u > \end{pmatrix}$$ $< Y_{u,d} >$ breaks flavor sym and → quark mixings:

- Flavor resides in the heavy quarks !!
- new flavor gauge bosons with TeV mass

Top partner in quark seesaw

- .RH t′ mixing to t can be large





- t′→Wb less likely than t′→t h