Parity Solution to Strong CP and Its Implications

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Plan of the talk

(i) Introduction

(ii) Possible problems with axion solution

(iii) Parity solution and implementation in the quark seesaw framework

(iii) Implications: *Neutrino masses, New scalars, Collider tests*

Naturalness problems of the standard model

- Two widely discussed ones are:

  (i) Higgs mass near weak scale

  (ii) Strong CP parameter tiny

  :

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Strong CP problem

- What is the strong CP problem ?
- Non-perturbative QCD effects→

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} + \theta_0 G\tilde{G}$$

- Theory with flavor: $\bar{\theta} = \theta_0 + \mathrm{Arg\ Det\ M_u M_d}$
- $\bar{\theta}$ violates P and CP → edm of neutron
- Current edm limits → $\bar{\theta} \leq 10^{-10}$
- No anthropic reasons for it to be small; so why is it so small?

Axion Solution

- A popular solution is to use axion

$$\mathcal{L}_{QCD} = \mathcal{L}^0_{QCD} + \bar{\theta} G\tilde{G} + \frac{1}{f} aG\tilde{G}$$ (Peccei-Quinn)

- → axion potential $V(\frac{a}{f_a} + \bar{\theta})$
- Ground state→ $(\frac{a}{f_a} + \bar{\theta}) = 0$; no strong CP violation
- Cosmology,SN→ $10^9 \text{ GeV} \le f_a \le 10^{12} \text{ GeV}$
- Predicts ultralight particle axion; $m_a \sim 10^{-6}\text{eV}$
- Postulate an axial $U(1)_{PQ}$ symmetry and axion is the Goldstone boson corresponding to it.

Gravity problem of U(1) axion

- All global symmetries are broken by non-perturbative Planck scale effects e.g. Blackholes
- At the effective Lagrangian level non-perturbative gravity effects induce Planck suppressed terms in e.g. $\mathcal{L}_{eff} = \beta\sigma^5/M_{Pl}$ +hc

→ $$V(a) = V_0(\frac{a}{f_a} + \bar{\theta}) + \frac{Im\beta f_a^5}{M_P}\sin\frac{a}{f_a}$$

- They generate large $\bar{\theta}$ unless their coefficient is

  $\beta < 10^{-52}$ (Kamionkowski et al'92, Holman et al'92; Barr, Seckel'92;)

Rescuing the axion

- (i) String theory possibility: there are no global symmetries in string theory but there are axion like particles in the gravity multiplet, H which couple universally to all gauge groups (Witten'84; Kim, Choi'86; Banks, Dine'96; Svrcek, Witten'06)

$$* \, da = H = dB - \omega_Y + \omega_L$$
$$\Delta a = * dH = *(R \wedge R - F \wedge F).$$

- However, scale of axion is string scale, conflicts with cosmology; requires additional inputs.
- Corrections to V(a) from string instanton effects ?

Higher dimensional axion

- Five dim. gauge theories can have a Chern-Simon term of the form (Choi)

$$\epsilon^{IJKMN} A_I F_{JK} F_{MN}$$

- A_5 protected by 5D gauge transformation and can be identified with axion and leads to $aG\tilde{G}$ term. Scale is no more constrained !
- However, there are also compactification corrections here- not under control !

Alternative solutions to axion

- (ii) Discrete symmetry solutions: CP (Nelson, Barr'86)

  CP is spontaneously broken; Not easy to get

  large CKM phase for quarks ? (Dine and Draper'15)

  -Also loop corrections can be large!!

- (iii) Parity solution: P: (Beg, Tsao'78; RNM, Senjanovic'78) ✓

  CKM built in right from the start:

Parity solution: Extend SM to Left-Right Model

- LR basics: Gauge group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- Fermions $\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$ $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$
- $g_L = g_R \rightarrow$ $L = \frac{g}{2}[\vec{J}_L{}^{\mu} \cdot \vec{W}_{\mu L} + \vec{J}_R{}^{\mu} \cdot \vec{W}_{\mu R}]$
- Parity a spontaneously broken symmetry $M_{W_R} \gg M_{W_L}$ (RNM, Pati,74; Senjanovic, RNM'75; Marshak, RNM;79)

Parity constraints on Yukawa coupling matrices

- Under parity, $\psi_L \leftrightarrow \psi_R$, $\phi \leftrightarrow \phi^\dagger$

$$\mathcal{L}_Y = h_{ij}\bar{\psi}_L\phi\psi_R + h.c.$$

- P-invariance implies that $h_{ij}^* = h_{ji}$
- Hermitean Yukawa matrices;
- Quark mass matrices: $M_q = h < \phi^0 >$
- $< \phi^0 >$ real → M_q hermitean;→

$$\boxed{\text{Arg Det } M_q = 0}$$

Parity solution to strong CP

- $$\bar{\theta} = \theta + \mathrm{Arg\ Det} M_u M_d$$

- Two steps:

  (i) in LR models parity implies that $\theta = 0$

  (ii) $M_{u,d} = M^{\dagger}_{u,d} \rightarrow \ \mathrm{Arg\ Det} M_u M_d = 0$

- If so, at tree level, no strong CP problem !

Challenge for this solution

- Need to have $< \phi^0 >$ real naturally !

- Loop corrections to $M_{u,d}$ must maintain its hermiticity until at least two loops !!

Minimal LR model for neutrinos

- LR bidoublet: $\phi = \begin{pmatrix} \phi_1^{\ 0} & \phi_2^{\ +} \\ \phi_1^{\ -} & \phi_2^{\ 0} \end{pmatrix}$
- Triplet to break B-L and generate seesaw: $\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix}$

$$\mathcal{L}_Y \ = \ h\bar{L}\phi R + \tilde{h}\bar{L}\tilde{\phi}R + fRR\Delta_R + h.c.$$

- Potential has one CPV terms→ $< \phi^0 >$ complex.

e.g. $\beta Tr(\phi^\dagger\tilde{\phi})\Delta_L^\dagger\Delta_L \ + \beta^*(L \to R)$

Implementing the parity solution

- Two ways around:

(i) Minimal left-right+ susy→ $< \phi^0 >$ real

(RNM, Rasin'96;Kuchimanchi'96)

(ii) Quark seesaw with new vectorlike fermions

(Babu, RNM'90)

Quark Seesaw model

- Add singlet fermions $U_{L,R},\ D_{L,R},\ E_{L,R}$
- Higgs structure minimal: Doublets: $\chi_L,\ \chi_R$

  + a P-even singlet S (no bi-doublet)
- Yukawa couplings:

$$\mathcal{L}_Y = h_{ij}\bar{Q}_{i,L}\chi_L U_R + h_{ij}\bar{Q}_{i,R}\chi_R U_L + D, E - terms$$

$$+ f_S^u S\bar{P}P + D, E....$$

- Vevs $v_{L,R,}$ v_S are naturally real

Quark seesaw

- Fermion masses in seesaw form

P→ $$M_{q,ij} = \begin{pmatrix} 0 & h_{ij} v_L \\ (h^\dagger)_{ij} v_R & f v_S \end{pmatrix}$$

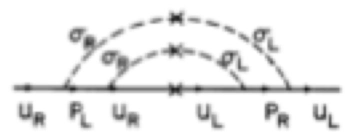
- Note now naturally $\bar{\theta}^{tree} = 0$

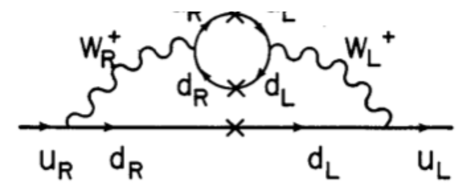
  since Arg. Det M_u M_d =0
- Solves strong CP without axion. (Babu, RNM'90)
- Check loop corrections:

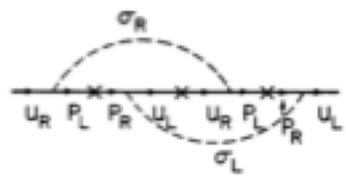
Estimating θ from loops

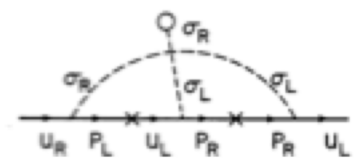
$$\delta\theta = Im\ \mathrm{Tr}\ \left[m_u^{-1}\delta m_u + m_d^{-1}\delta m_d\right]$$

- 1-loop $\quad \delta\theta = 0$
- As is 2-loop
- (Babu, RNM'89)









- 3-loop small

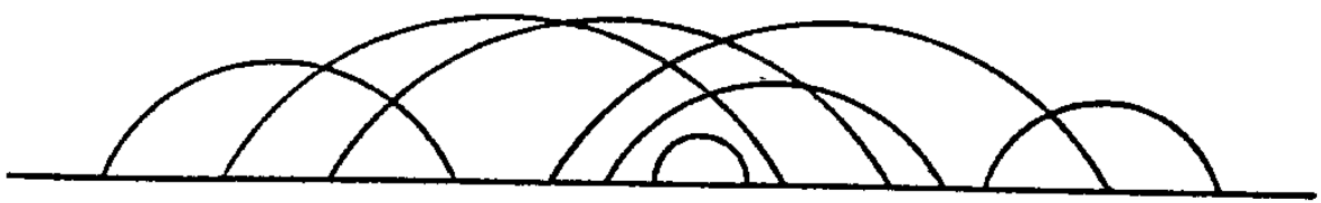
$$\bar{\theta} < \left(\frac{1}{16\pi^2}\right)^3 \left(\frac{v_L}{v_R}\right)^2 f(h,g)$$

(v_L / v_R) suppression

- $v_R \rightarrow \infty$, implies $v_s \rightarrow \infty$ and model goes to SM;
- In SM, we know, $\bar{\theta}$ arises at 7-loop level

(Ellis, Gaillard)

- Hence the result.



Planck scale corrections and Limit on WR scale

- 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 $\bar{\theta} < 10^{-10}$ →

$$\delta\theta = \frac{v_L v_R}{m_u M_{Pl}} \leq 10^{-10} \Rightarrow v_R \leq 100 \text{ TeV}$$

- Low scale W_R – of interest for colliders

Other consequences of quark seesaw

- Fermion masses are given by (Berezhiani'84; Davidson,Wali'87…)

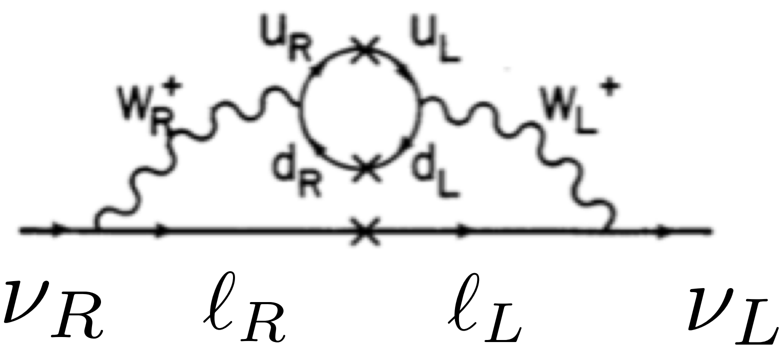
$$m_q \simeq \frac{h^2 v_L v_R}{M_Q}$$

- Fundamental Yukawas don't have to be as small as in SM- e.g. for electrons, h > $10^{-2.5}$

  rather than $10^{-5.5}$ as in SM.
- Since $hh^\dagger$ is an arbitrary hermitean matrix, it easily leads to CKM mixing

Neutrino masses

- How do neutrino masses arise?
- Dirac mass comes from two loop diagram.



- $m_{D_i} \sim 10^{-9} m_{\ell_i}$ ~ eV *(U_{PMNS} =1; solar mass wrong)*
- Add singlet heavy fermions $\mathcal{N}_{L,R}$ (makes model Q-L symmetric)

Dirac Neutrino Possibility

- Simplest possibility is: no Majorana masses for $\mathcal{N}_{L,R}$
- Dirac mass matrix: $M_{\nu,\mathcal{N}} = \begin{pmatrix} m^{loop} & hv_L \\ h^\dagger v_R & M_{\mathcal{N}} \end{pmatrix}$

$$m_\nu \sim \frac{hh^\dagger v_L v_R}{M_{\mathcal{N}}} - m^{loop}$$

- Choose $h \sim h_e \sim 10^{-5.5}$

ν_R contribution to N_{eff} for Dirac case

- For few TeV $W_{R,}$ ν_R decouples above T_{QCD} ~.2 GeV;

$$\Delta N_{eff} \sim 0.3$$

- Current limits: N_{eff} ~3-3.5 Planck (1sigma)
- Tension between Planck and direct measurement of H_0
- Euclid has more sensitivity can test the model

Alternative possibility: (a) Pseudo-Dirac

- Needed if we want to do leptogenesis
- Add small Majorana mass $\delta m_{\mathcal{N}_L}$ for $\mathcal{N}_L$
- Induces pseudo-Dirac mass δm_ν to $\nu_L - \nu_R$
- Constrained by solar data and cosmology to be

$$\delta m_\nu \leq 10^{-9}\ eV$$ (de Gouvea, Huang, Jenkins'10)

- Implies $\delta m_{\mathcal{N}_L} \leq 10^{-6}\ GeV$
- Consistent with BBN
- Observation of $\beta\beta_{0\nu}$ decay will rule out these parameter domains of model!

(b) Majorana

- Suppose: $\delta M_{\mathcal{N}_{\mathcal{L}}}, \delta M_{\mathcal{N}_{\mathcal{R}}} \gg M_{\mathcal{N}} \gg h_\nu v_{L,R}$
- Active ν_L and sterile ν_R Neutrinos Majorana

$$\frac{m_{\nu_L}}{m_{\nu_R}} \sim \left(\frac{v_L}{v_R}\right)^2$$

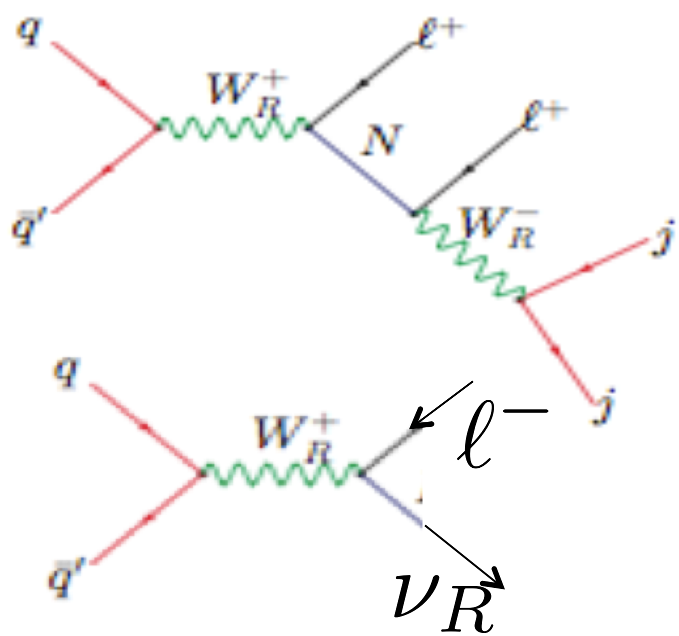
- Predicts Sterile neutrinos with mass ~10 eV, 1 eV and
- Mixings ~ 0.01 - 0.001→ Conflicts with BBN – most likely disfavored (under investigation)

Distinguishing collider signal for neutrinos

- Conventional TeV LR seesaw: collider signal:

$$pp \to \ell\ell jj$$

(Keung, Senjanovic'83)



- This model:

$$pp \to \ell \not{E}$$

- No diboson signal since WL-WR mixing is 2-loop effect- tiny

(Adding bi-doublet destroys strong CP solution)

Other Phenomenology:

(i) New scalars:

(ii) New fermions:

New Scalars

- Model has only three neutral Higgs:
- SM Higgs: $h = \mathrm{Re}\ \chi_L^0$
- All properties same as SM Higgs to high accuracy
- Second Higgs: $\sigma_R = \mathrm{Re}\ \chi_R^0$; M ~ TeV

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

Third scalar S: coupled to vectorlike fermions

- Can be identified with the 750 GeV diphoton "resonance" at CMS and ATLAS (Dev, Zhang, RNM'15,JHEP)

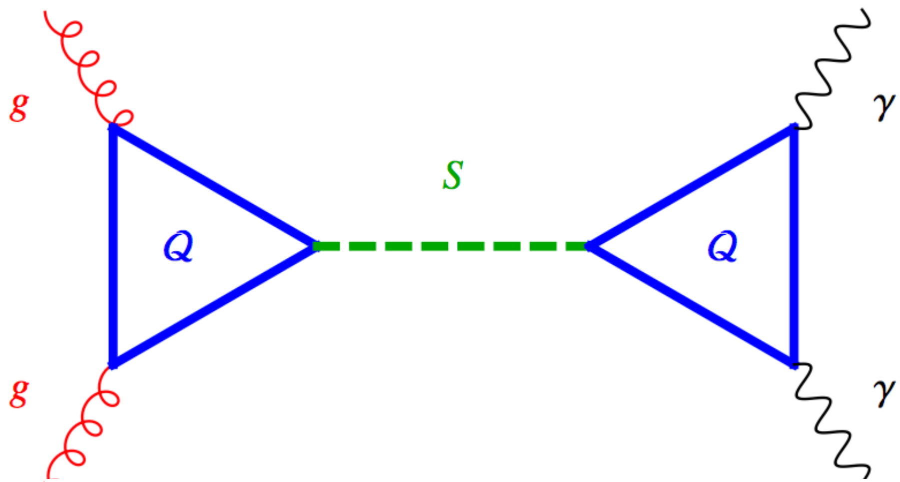
- How? Data: 2-photon signal cross sections:

$$(6 \pm 3)\mathrm{fb}(\mathrm{CMS}); (10 \pm 3)\mathrm{fb}\ (\mathrm{ATLAS})$$

- Width unknown. *CMS prefers ~GeV;ATLAS ~45 GeV*

- Puts limits on the scales

Production and decay in this model



Blue lines: heavy Vectorlike quarks

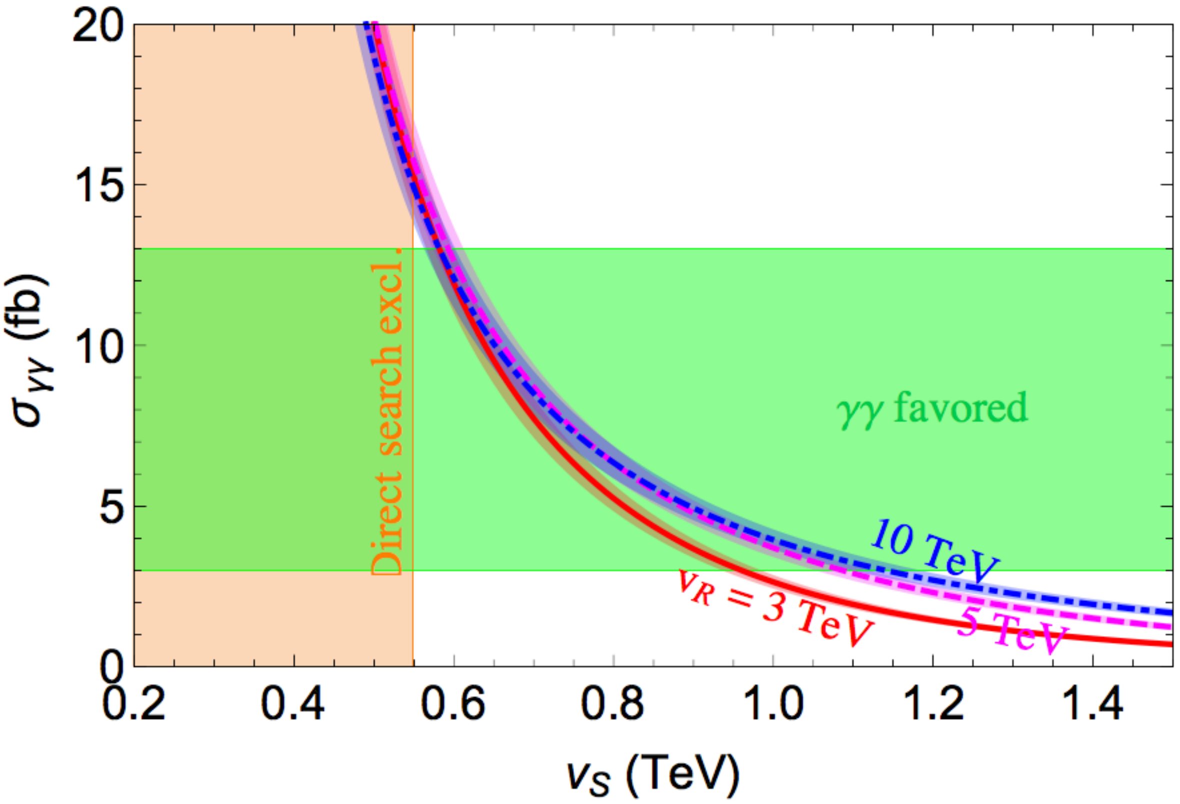
$$\sigma(pp \to \gamma\gamma) = \frac{C_{gg}}{M_S s} \Gamma_{gg} \mathrm{Br}_{\gamma\gamma}$$

C_{gg} = parton integral: 174 at 8 TeV to 2137 at 13 TeV

Parameter domain where it works:

- gg-fusion production rate adequate→ $f_F > 0.5$
- 750 GeV fit works for $v_S < 1.2$ TeV since gg→S rate goes like v_s^{-2}
- $m_t \to v_R \sim v_S$: gives an upper limit on v_R
- Property: t-T mixing ~0.1
- Allows S→tt-bar decay

Correlating on v_R and v_S



Production and decay of S

- .

	$v_R = 3$ TeV	$v_R = 5$ TeV
f_F (input)	1	1
v_S [GeV] (input)	800	1000
$\sigma(gg \to S)$ [pb]	1.61	0.95
$\Gamma_{\text{total}}(S)$ [GeV]	0.21	0.071
signal cross section [fb]		
$t\bar{t}$	423	122
gg	1173	825
$\gamma\gamma$	5.3	3.7
γZ	3.2	2.3
ZZ	0.48	0.34

Predictions of this theory for S

- Narrow width (~ GeV)

- Generic prediction for SM singlet scalar coupled to vector-like singlet fermions:

$$\Gamma_{\gamma\gamma} \ : \ \Gamma_{Z\gamma} \ : \ \Gamma_{ZZ} \ = \ 1 \ : \ 2\tan^2\theta_w \ : \ \tan^4\theta_w$$

$$\Gamma_{WW} = 0$$

Vector-like quarks in colliders

- Dominant decay modes:

$$pp \to T\bar{T}, Q\bar{Q}$$

$$T \to bW, th, tZ$$

$$Q \to dW, uh, uZ$$

- Current limits: T: 900 GeV (ATLAS13) (→qW)
  B: 730 GeV; Q: 788 GeV

An interesting mode for T-vectorlike quarks

- Collider tests: $pp \to T\bar{T}$ $(T \to th, Wb, Zt)$
- $$\left.\begin{array}{l} T \to th \to b\bar{b} \\ \qquad\;\; \hookrightarrow b\ell\nu \end{array}\right\} \longrightarrow \text{3b}$$

- Signal: pp→ 6 b+ 2l+missing E.

Origin of S and higher unification

- If U, D and E are vector-like why do we need a scalar to give mass to them ?
- We are taking our model as an effective theory.

In the true UV complete theory, they might be chiral instead of vectorlike and cannot form a mass term: e.g. $u_L\, u_R$ in effective theory below the weak scale can exist but once weak interactions are included, they cannot without the Higgs.

Example of a higher scale theory: GUT embeddings

$$SU(5)_L \times SU(5)_R$$

(Davidson,Wali'87;Cho'93;RNM'96)

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L,L} \times U(1)_{B-L,R}$$

$\mathrm{Chirally\ split\ B-L}$

(Cao,Chen,Gu'2015)

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

$$SU(2)_L \times U(1)_Y$$

Fermions fit right in

P=U;

N=D

$$\psi = \begin{pmatrix} D_1^c \\ D_2^c \\ D_3^c \\ e^- \\ \nu \end{pmatrix} ; \ \chi = \begin{pmatrix} 0 & U_3^c & -U_2^c & u_1 & d_1 \\ -U_3^c & 0 & U_1^c & u_2 & d_2 \\ U_2^c & -U_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & E^+ \\ -d_1 & -d_2 & -d_3 & -E^+ & 0 \end{pmatrix}$$

$$\psi^c = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \\ e^+ \\ \nu^c \end{pmatrix} ; \ \chi^c = \begin{pmatrix} 0 & U_3 & -U_2 & u_1^c & d_1^c \\ -U_3 & 0 & U_1 & u_2^c & d_2^c \\ U_2 & -U_1 & 0 & u_3^c & d_3^c \\ -u_1^c & -u_2^c & u_3^c & 0 & E^- \\ -d_1^c & -d_2^c & -d_3^c & -E^- & 0 \end{pmatrix}$$

Strong CP solution works (in progress).

Summary

- Quark seesaw with multi-TeV scale W_R could be an alternative solution to strong CP problem without need for an axion and no gravity issues.
- Tests: (i) Vectorlike quarks an essential part of this solution; (ii) Collider signal different from conventional LR seesaw; (iii) Preference for neutrinos being Dirac or Pseudo-Dirac; (iv) No WR mediated dibosons
- → New neutral scalars, one of which could possibly be responsible for the 750 GeV excess at LHC13.

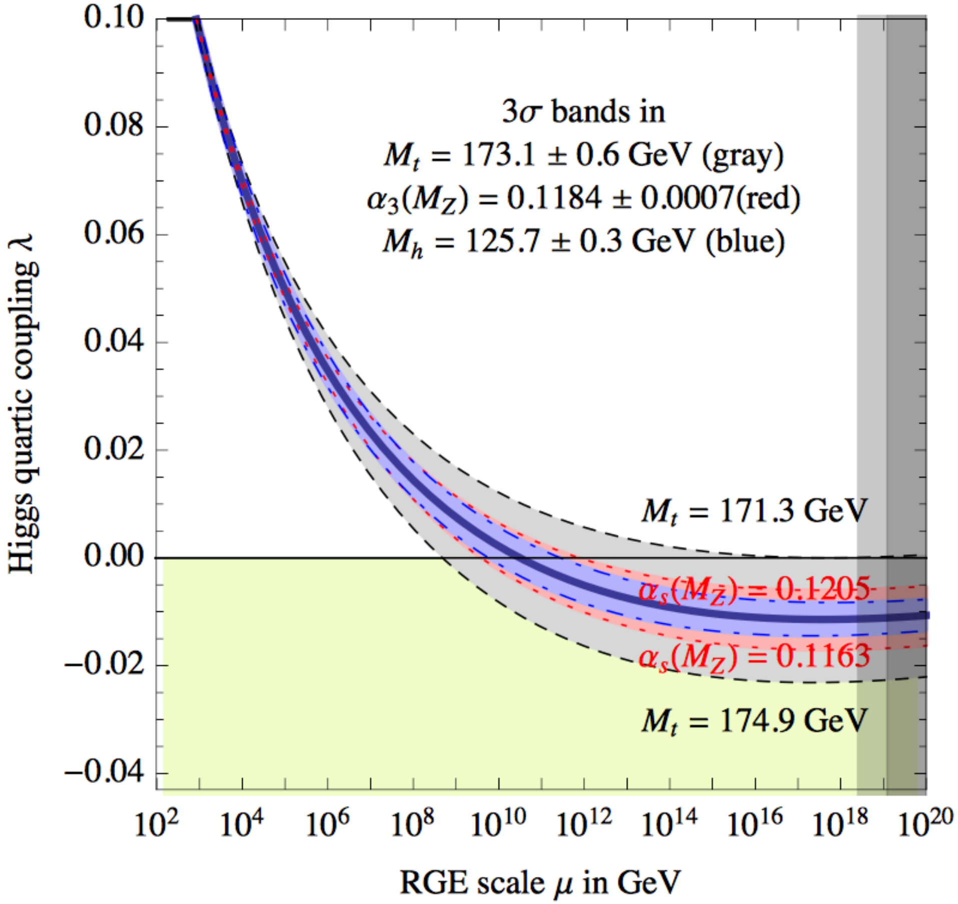
$$Thank\ you\ for\ your\ attention\ !$$

Spinoff: New scalars and Vacuum stability

- SM $m_h = 125\ \mathrm{GeV}$

$$\lambda \sim \frac{1}{8} \to$$

- Vacuum instability



LR Quark seesaw cure

- For weak coupling of S to other Higgs,

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

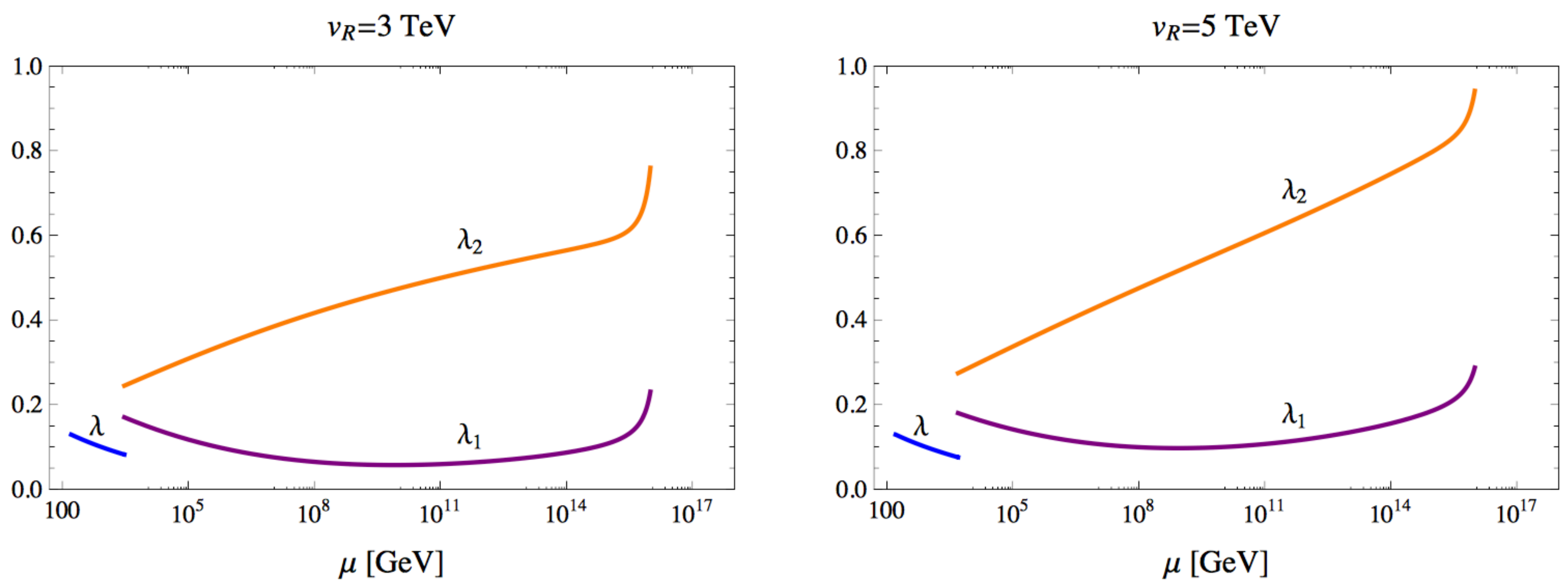
- Higgs masses $M_h^2 = 2\lambda_1 \left(1 - \frac{\lambda_2^2}{4\lambda_1^2}\right) v_L^2$

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

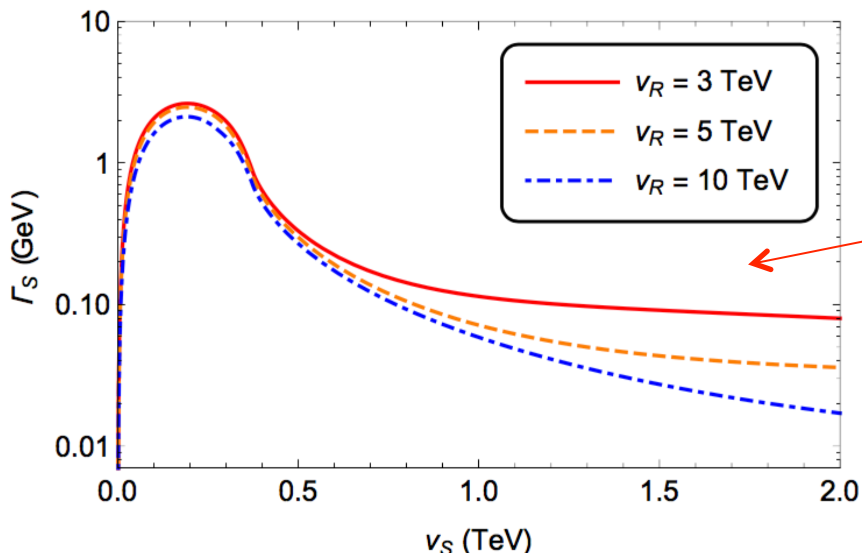
- So $\lambda_1(v_R)$ can be larger.

Resolves the vacuum stability issue of SM Higgs

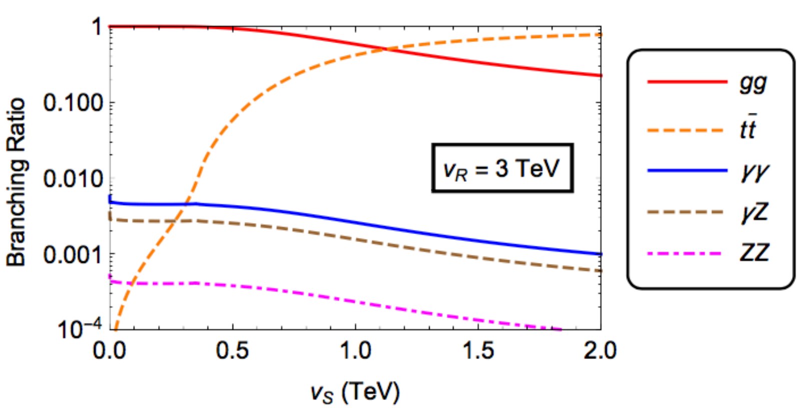
- . None of the couplings go negative till GUT scale (for $f_S << 1$) !! (RNM, Yongchao Zhang'14)

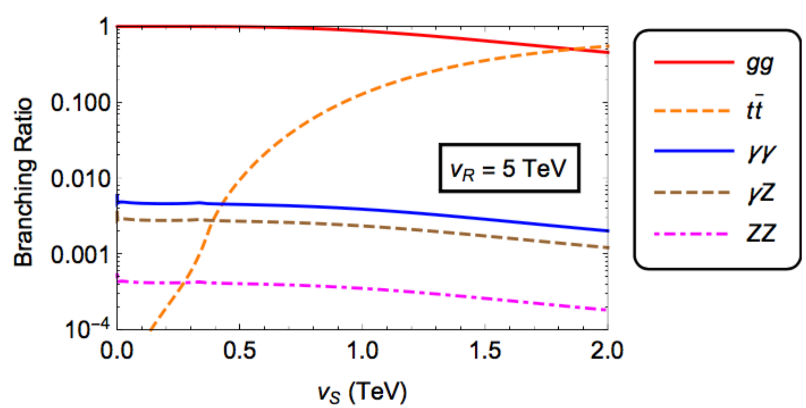


Decays as a function of v_S



Narrow width a prediction for 750 GeV scalar





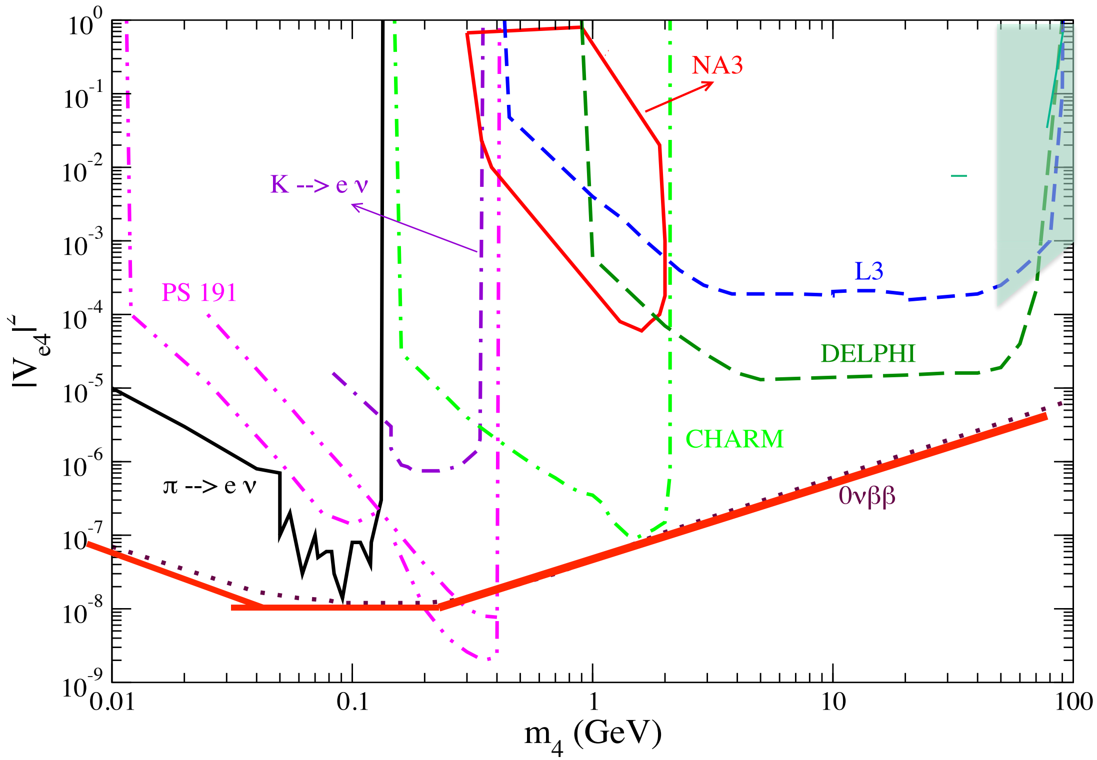
Properties of RH neutrinos

- Distinguishing property from usual low scale seesaw models:
- SM and LR seesaw:

$$|U_{eN}|^2 \sim \frac{m_\nu}{M_N} \sim 10^{-10}\left(\frac{10\ \mathrm{GeV}}{M_N}\right)$$

- Quark seesaw LR: $|U_{eN}|^2 \sim 10^{-18}$ for $M_N \sim$ GeV
- GeV M_N allowed by most data
- N decays via W_R exchange

Constraints RH Neutrino M_N in the lower mass range



(Atre, Han, Pascoli, Zhang)

Dev, Francischini, RNM'12 ;

Gago,Hernandez,Perez,Losada,Briceno'15

Prediction for neutron edm

- Edm of neutron <-- edm of up and down quarks; same diagram as for θ but only $(M_{u,d})_{11.}$
- One loop $\delta M_{u,d} = \delta M^{\dagger}_{u,d}$
- $(M_{u,d})_{11}$ real and no N edm at one loop level.
- Two loop contribution non-zero $d_n \sim 10^{-27}$ -10^{-28} ecm.