Theoretical and Experimental aspects of the Electroweak-scale right-handed neutrino model with displaced vertices as distinct signatures

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The case for the missing right-handed neutrinos

- A sense of "doom" seems to pervade over the particle physics community: After spending billions of dollars building the LHC, the only thing that we have found- and that "may be" all- is the SM Higgs? No signs of Physics beyond the SM (BSM)?
- Patient please! We still have a few more years of data taking and data analysis. Who knows what will show up? This is what this workshop is all about!
- First of all, it is far from clear that the 125-GeV scalar is the lonely SM Higgs.
- Secondly, it is not true that we have not seen any sign of physics BSM: neutrino oscillations ⇒ neutrino masses ⇒ BSM ⇒ Most likely the existence of right-handed neutrinos ν_R.
- Where are they? There are indirect experimental proofs that they exist. Have we been up-until-now going on a "wild-goose chase"?

Outline

- Where we are now and where we might be heading.
- The origin of neutrino masses can be naturally incorporated in Collider Physics if right-handed neutrinos are non-sterile (in other words fertile) ⇒ The Electroweak-scale right-handed neutrino model (EW-ν_R model) or simply the mirror fermion model.
- What has the EW-ν_R model achieved so far? Experimentally, what are its most characteristic signals? What might be the most effective ways to search for right-handed neutrinos and other mirror fermions of the model?
- Theoretically, the structure of the EW-ν_R model yields a surprising new solution to an old problem: the strong CP problem, without the need for an axion.

Brief summary of Collider Physics results

- "Brief" here means basically talking about the 125-GeV scalar
- What have we found? A 125-GeV scalar that looks like the SM Higgs.
- Actually, the only thing that we can determine is the signal strength: $\mu = (\sigma \times BR)_{model}/(\sigma \times BR)_{SM}$. To really ascertain that the 125-GeV scalar is truly the SM Higgs, one needs to know its couplings with other particles and with itself (e.g. upcoming studies of di-Higgs production,..). Many of these properties will have to wait for the construction of a Higgs factory!
- The dearth of any new signals other than the 125-GeV scalar perhaps should prompt us to look for new search strategies for Physics BSM. Have we been putting all the eggs in one basket up until now?

Brief summary of Collider Physics results

- On the other hand, the only BSM that we know of now is the presence of neutrino masses through neutrino oscillations! Can we try to probe that BSM at Colliders and try to search for ν_R's?
- What prevented us from doing it so far? All generic scenarios of the seesaw mechanism have right-handed neutrinos inert under the SM. In addition, the mass scales involved are very large, making it impossible to test the seesaw mechanism at energies below a few TeV's. Variants of generic scenarios are very complicated and hard to test.
- The EW-ν_R model provides a natural framework for incorporating neutrino physics into Collider Physics.
- LHC: Right-handed neutrinos are knocking at your door!

The EW-ν_R model

- Lee and Yang on Parity Violation: "If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry.." PR104, 254, October 1956.
- It is based *solely* on the SM gauge group $\boxed{SU(3)_C \times SU(2)_W \times U(1)_Y}$.
- It contains mirror quarks and leptons out of those right-handed neutrinos emerge, are naturally non-sterile and have Majorana masses proportional to the electroweak scale $\Lambda_{EW} \sim 246 GeV$. The seesaw mechanism can be tested at colliders such as the LHC.
- It satisfies electroweak precision data represented by the parameters S, T and U. In fact, any BSM model is required to satisfy this first criterion.

The EW-ν_R model

- It accommodates the 125-GeV scalar. In fact, it provides two distinct scenarios for the 125-GeV scalar: *Dr Jekyll* (very SM-like) and *Mr Hyde* (very different from the SM Higgs), both of which give signal strengths consistent with experiment. It predicts heavier scalars and pseudo-scalars.
- A model of lepton masses and mixings with a discrete non-abelian symmetry A_4 was constructed to reproduce the PMNS mixing matrix.
- Using the above construction, we applied the model to calculate the processes $\mu \rightarrow e\gamma$ and μ to e conversion and obtained strong constraints on the Yukawa couplings g_{Sl} which determine the decay (into SM leptons) lengths of mirror leptons.
- Contributions to the electric dipole moment of the electron were also computed and compared with the present bound.

The EW-ν_R model

- Analyses of productions and decays of mirror quarks and leptons have been performed with various constraints imposed on the model from existing experimental data. However, constraints coming from $\mu \to e\gamma$ and μ to e conversion generally requires $g_{Sl} < 10^{-4}$ and from $\bar{\theta}$ (strong CP) requiring $g_{Sq} < g_{Sl}$. This implies that characteristic signatures in the searches for mirror fermions will be *displaced vertices*!
- The presence of mirror quarks and their mixings with SM quarks along with the associated global symmetries provide a new solution to the strong CP problem without an axion. $\bar{\theta}$ does not have to vanish! $\bar{\theta}$ is found to be proportional to the neutrino mass and is small because the neutrino mass is small.

Summary of the EW-ν_R model

- Gauge group: $\boxed{SU(3)_C \times SU(2)_W \times U(1)_Y}$. Notice the subscript W instead of L.
- Fermions: SM: $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$; $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$; e_R; u_R, d_R; Mirror: $l_R^M = \begin{pmatrix} \nu_R^M \\ e_R^M \end{pmatrix}$; $q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}$; e_L^M; u_L^M, d_L^M.
- Scalars:
  * Doublet Higgs fields: $\Phi_1^{SM}(Y/2 = -1/2)$, $\Phi_2^{SM}(Y/2 = +1/2)$ coupled to SM fermions, and $\Phi_1^M(Y/2 = -1/2)$, $\Phi_1^M(Y/2 = +1/2)$ coupled to mirror fermions with $\langle \Phi_1^{SM} \rangle = (v_1/\sqrt{2}, 0)$, $\langle \Phi_2^{SM} \rangle = (0, v_2/\sqrt{2})$ and $\langle \Phi_1^M \rangle = (v_1^M/\sqrt{2}, 0)$, $\langle \Phi_2^M \rangle = (0, v_2^M/\sqrt{2})$.
  *Triplet Higgs fields:

Summary of the EW-ν_R model

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}$$

$\xi\ (Y/2 = 0) = (\xi^+, \xi^0, \xi^-)$ with $\langle \chi^0 \rangle = \langle \xi^0 \rangle = v_M$ in order to preserve Custodial Symmetry (that guarantees $M_W^2 = M_Z^2 \cos^2\theta_W$ at tree level. Here $(\sum_{i=1,2} v_i^2 + v_i^{M,2}) + 8 v_M^2 = (246\, GeV)^2$.

*Singlet Higgs fields: ϕ_S: We require 4 ϕ_S for the construction of a neutrino mass matrix within the framework of A_4.

As we shall see below, this singlet scalar sector is interesting both in terms of giving distinctive signatures (displaced vertices) in the search for mirror quarks and leptons . The processes $\boxed{l_R^M \rightarrow l_L + \phi_S}$ and $\boxed{q_R^M \rightarrow q_L + \phi_S}$ play a key role with ϕ_S "appearing" as missing energy.

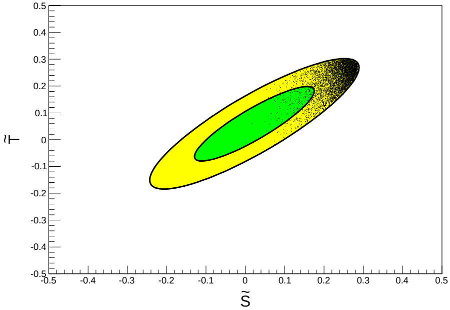
Summary of the EW-ν_R model

- Majorana mass: Lepton-number violating term
  $L_M = g_M \, l_R^{M,T} \; \sigma_2 \; \tau_2 \; \tilde{\chi} \; l_R^M \Rightarrow$ Right-handed neutrino Majorana mass
  $\boxed{M_R = g_M v_M} \Rightarrow \boxed{M_R < \Lambda_{EW} \sim 246 GeV}$: Main point.
- Dirac mass: Lepton-number conserving term
  $\mathcal{L}_S = -g_{Sl} \, \bar{l}_L \; \phi_S \; l_R^M + \mathrm{H.c.} \Rightarrow$ neutrino Dirac mass $\boxed{m_\nu^D = g_{Sl} \; v_S}$
  where $\boxed{\langle \phi_S \rangle = v_S}$. Crucial in the discussion of the phenomenology of the model and the strong CP problem.
- Charged SM and mirror leptons obtain masses by coupling to $\Phi_{1,2}^{SM}$ and $\Phi_{1,2}^{M}$respectively (similarly for SM and mirror quarks).
- One particular term in the Lagrangian which is crucial for the searches of mirror fermions and for the strong CP problem is given by (similar for the leptons):

$$\boxed{\mathcal{L}_{mixing} = g_{Sq} \bar{q}_L \phi_S \bar{q}^M{}_R + g_{Su} \bar{u}_L^M \phi_S u_R + g_{Sd} \bar{d}_L^M \phi_S d_R + H.c..}.$$

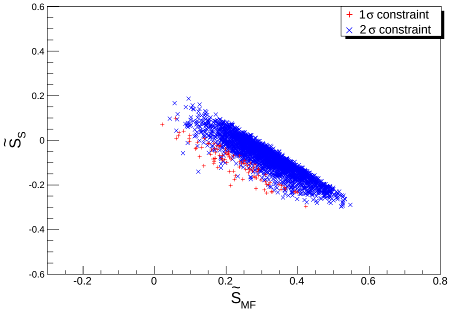
Summary of the EW-ν_R model: Precision constraints

Fig. 1 and 2 are the 1σ and 2σ constraints. $\tilde{T}$ and $\tilde{S}$ are the total contributions (mirror fermions plus scalars) after subtracting out the SM contributions.



Summary of the EW-ν_R model: Precision constraints

$\tilde{S}_S$ and $\tilde{S}_{MF}$ are the contributions to S from the scalars (mainly the triplets) and the mirror fermions.



Summary of the EW-ν_R model: Precision constraints

- 2016 PDG value for $\tilde{S} = 0.07 \pm 0.08$
- Notice that, for a large range of parameters, the contribution to $\tilde{S}_S$ from Triplet scalars is generally negative and large (see the previous figure)!
- If only triplet scalar is present ⇒ very small region of parameter space for $\tilde{S}_S$ is allowed ⇒ fine-tuning problem! The much larger parameter space which allows mass splitting inside the triplet has large and negative values for $\tilde{S}_S$ which need to be cancelled by similar positive amount coming from another sector such as the mirror fermion sector! One cannot play around with triplet Higgs without experimental consequences!

Summary of the EW-ν_R model: 125-GeV scalar

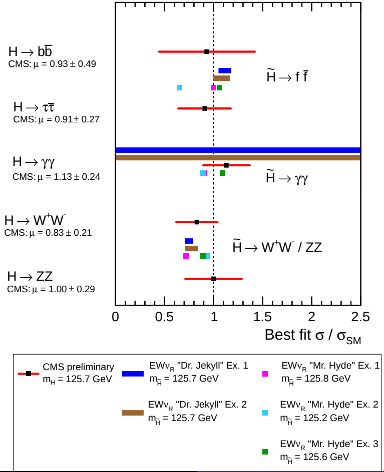
In one version of the model, after SSB, one has the following physical scalars transforming under the custodial symmetry SU(2) as:

$$\begin{aligned} \text{five-plet (quintet)} &\rightarrow H_5^{\pm\pm},\; H_5^{\pm},\; H_5^0; \\ \text{triplet} &\rightarrow H_3^{\pm},\; H_3^0; \\ \text{triplet} &\rightarrow H_{3M}^{\pm},\; H_{3M}^0; \\ \text{three singlets} &\rightarrow H_1^0,\; H_{1M}^0,\; H_1^{0\prime}, \end{aligned} \tag{1}$$

The lightest combination, $\widetilde{H}$, of the three singlets represents the 125-GeV scalar.

A scan over the parameter space of the model yielded *two interesting scenarios* for the 125-GeV scalar: 1) *Dr Jekyll*'s scenario in which $\widetilde{H} \sim H_1^0$ meaning that the SM-like component $H_1^0 = \phi_2^{0r}$ is *dominant*; 2) *Mr Hyde*'s scenario in which $\widetilde{H} \sim H_1^{0\prime}$ is dominant (very un-SM like).

Summary of the EW-ν_R model: 125-GeV scalar



Summary of the EW-ν_R model: 125-GeV scalar

To really know what the 125-GeV scalar truly is, we need to measure the partial decay widths $\Rightarrow$ Higgs factory!

Search for mirror fermions: Characteristic signatures

Two important characteristic signatures to pay attention to in the search for ν_R's and accompanying mirror fermions.

I) Lepton-number violating signals at high energy: Like-sign dileptons from the decays of $\nu_R \nu_R$.

- Suppose some ν_R are heavier than some e^M_R:
  $\nu_{Ri} \rightarrow e^M_{Rj} + W^+$ followed by $e^M_{Rj} \rightarrow e_{Lk} + \phi_S$.
- $\nu_R i + \nu_{Ri} \rightarrow e_{Lk} + e_{Ll} + W^+ + W^+ + \phi_S + \phi_S$ with $k = l$ or $k \neq l$
- Like-sign dileptons $e_{Lk} + e_{Ll}$ plus 4 jets (from 2 W) plus missing energies (from ϕ_S) $\Rightarrow$ Lepton-number violating signals!

Search for mirror fermions: Characteristic signatures

II) Decays of mirror fermions into SM fermions plus "missing energy" ϕ_S occur at displaced vertices (decay lengths > 1mm).

- Mirror leptons: $\boxed{l_R^M \rightarrow l_L + \phi_S}$. The decay depends on the Yukawa coupling g_{Sl}.
- Calculations of $\mu \rightarrow e\gamma$ and μ to e conversion in the model give a general constraint on those Yukawa couplings $\boxed{g_{Sl} < 10^{-4} \Rightarrow \text{Could have decay lengths} > 1\text{mm}}$! How does one handle that?
- The appearance of $\boxed{\text{like-sign dileptons}}$ $(e^- e^-, \mu^- \mu^-, \tau^- \tau^-, e^- \mu^-, ...)$ could be at a $\boxed{\text{displaced vertices}}$.

Search for mirror fermions: Characteristic signatures

- How about mirror quarks?
- $\boxed{q_R^M \to q_L + \phi_S}$: The decay length will depend on the Yukawa couplings g_{Sq}. Unlike the mirror lepton cases, there are no direct or indirect experimental constraints g_{Sq}.
- However, the structure of the EW-ν_R model contains elements that provide a solution to the strong CP problem!
- Seesaw in the EW-ν_R model $\Rightarrow$ Mixings between SM and Mirror fermions with imposed extra global symmetries to make seesaw work $\Rightarrow$ A simple axionless solution to the strong CP problem. $\bar{\theta}$ is found to be $\propto$ neutrino masses and is naturally small.
- Constraint on $\bar{\theta}$ $\Rightarrow$ Constraint on $g_{Sq} < g_{Sl}$ $\Rightarrow$ Displaced vertices in mirror quark decays.

The strong CP problem: Brief review

- The vacuum of QCD is complicated. 't Hooft: The proper gauge-invariant vacuum is characterized by an "angle"
  $|\theta\rangle = \sum_n \exp(-\imath n\,\theta)|n\rangle$
  n: Winding number.
- Vacuum-to-vacuum transition amplitude $\langle 0|0\rangle$ where S_{gauge} appears in the path integral $\Rightarrow$ $\langle\theta|\theta\rangle$ with an effective action
  $S_{eff} = S_{gauge} + \theta_{QCD}\,(g_3^2/32\pi^2)\int d^x\, G_a^{\mu\nu}\,\tilde{G}^a_{\mu\nu}$
  where the second term violates CP. (It's like $\vec{E}.\vec{B}$ where $\vec{E}$ and $\vec{B}$ have opposite signs under CP.)
- What is wrong with that?
- The CP-violating term contributes to the neutron electric dipole moment as
  Th.: $d_n \approx 5.2 \times 10^{-16}\theta_{QCD}\, e - cm$; Exp.: $|d_n| < 2.9 \times 10^{-26}\, e - cm$

The strong CP problem: Brief review

- $\theta_{QCD} < 10^{-10}$. Why is it so small? That is the strong CP problem.
- Worse still: Diagonalization of quark mass matrices ⇒ A chiral rotation of $U(1)_A$(part of the diagonalization matrices) which adds another "angle" such that
  $\bar{\theta} = \theta_{QCD} + ArgDetM$
  Reason: Jackiw and Rebbi: A chiral rotation $\tilde{Q}_5$:
  $\exp(\imath\alpha\tilde{Q}_5)|\theta\rangle = |\theta + \alpha\rangle$.
- Solution to the strong CP problem: How to make 1) $\theta_{QCD} = 0$, 2) $ArgDetM = 0$?
- Equally important: How to test that solution experimentally!

The strong CP problem: Brief review

- Peccei and Quinn solution:
  Extra global symmetry $U(1)_{PQ}$ (chiral)
- P-Q Toy model: Single flavor ψ interacting with a scalar ϕ ; Chiral symmetry $U(1)_A$ (or $U(1)_{PQ}$). Lagrangian invariant under a chiral rotation
  $\psi \to \exp(\imath\sigma\gamma_5)\psi$; $\phi \to \exp(-\imath 2\sigma)\phi$
- Jackiw-Rebbi: $\theta_{QCD} \Rightarrow \theta_{QCD} - 2\sigma \Rightarrow$ All vacuua are equivalent $\Rightarrow$ one can rotate θ_{QCD} to zero! No CP violation!
- Peccei and Quinn have proved that 1) $\langle\phi\rangle = 0 \Rightarrow$ No CP violation; 2) even if $\langle\phi\rangle \neq 0$ No CP violation if $\bar{\theta}$ is replaced by an axion field $a(x)$ where the minimum of an (quite complicated) effective potential is where the effective θ is zero.
- Visible axion ruled out by beam dump experiment. Invisible axion not found after more than 30 years or so.

The strong CP problem: Brief review

- There are several axionless models for the strong CP problem: Nelson, Barr,...

Neutrinos and the strong CP problem

Ingredients of the EW-ν_R model which help solve the strong CP problem without an axion.

- Mirror fermions.
- Mixing of mirror with SM fermions $\Rightarrow$ Dirac mass of neutrinos through $g_{Sl}\bar{l}_L \phi_S l_R^M$.
- A global symmetry $U(1)_{SM} \times U(1)_{MF}$ was imposed to prevent terms such as $\bar{l}_L \tilde{\chi} l_R^M$ (Dirac mass too big); $l_L^T\ \sigma_2\ \tau_2\ \tilde{\chi}\ l_L$ (gives rise to unwanted $\nu_L^T \nu_L$),..which spoil the seesaw mechanism.

What do the above ingredients have to do with the strong CP problem?

Neutrinos and the strong CP problem

- Most of salient points concerning the solution to the strong CP problem can be obtained with a toy model with one family.
- Relevant Yukawa interactions
  $\mathcal{L}_{mass} =$
  $g_u \bar{q}_L \Phi_1^{SM} u_R + g_d \bar{q}_L \Phi_2^{SM} d_R + g_u^M \bar{q}_R^M \Phi_1^M u_L^M + g_d^M \bar{q}_R^M \Phi_2^M d_L^M + H.c.\,,$
  $\mathcal{L}_{mixing} = g_{Sq} \bar{q}_L \phi_S q_R^M + g_{Su} \bar{u}_L^M \phi_S u_R + g_{Sd} \bar{d}_L^M \phi_S d_R + H.c.\,.$
- Step 1 of the solution to strong CP (Peccei-Quinn): Use a chiral symmetry to rotate away θ_{QCD}.
  $\mathcal{L}_{mixing}$ and $\mathcal{L}_{mass}$ are invariant under: $q \rightarrow \exp(\imath \alpha_{SM} \gamma_5) q$; $q^M \rightarrow \exp(\imath \alpha_{MF} \gamma_5) q^M$; $\phi_S \rightarrow \exp(-\imath (\alpha_{SM} + \alpha_{MF})) \phi_S$ under the chiral symmetries $U(1)_{A,SM} \times U(1)_{A,MF}$ contained in $U(1)_{SM} \times U(1)_{MF}$. Jackiw-Rebbi: $\theta_{QCD} \rightarrow \theta_{QCD} - (\alpha_{SM} + \alpha_{MF})$
- All vacuua are equivalent and one can choose the CP-conserving vacuum $\theta_{QCD} - (\alpha_{SM} + \alpha_{MF}) = 0$.

Neutrinos and the strong CP problem

- Notice that g_u, g_d, g_{u^M}, g_{d^M}, g_{Sq}, g_{Su} and g_{Sd} can, in general be complex. If we absorb the phases into u_R, u_L^M, d_R and d_L^M to make the *diagonal* elements of the (2×2) up and down mass matrices *real* then the *off-diagonal* elements stay *complex*.

$$\mathcal{M}_u = \begin{pmatrix} m_u & |g_{Sq}| v_S \exp(\imath\theta_q) \\ |g_{Su}| v_S \exp(\imath\theta_u) & M_u \end{pmatrix} \qquad (2)$$

$$\mathcal{M}_d = \begin{pmatrix} m_d & |g_{Sq}| v_S \exp(\imath\theta_q) \\ |g_{Sd}| v_S \exp(\imath\theta_d) & M_d \end{pmatrix} \qquad (3)$$

Neutrinos and the strong CP problem

- Step 2 of the solution to the strong CP problem: Calculation of $ArgDet\mathcal{M}_u\mathcal{M}_d$. Call that θ_{weak}.
- $\boxed{\theta_{Weak} \approx -(r_u \sin(\theta_q + \theta_u) + r_d \sin(\theta_q + \theta_d))}$

  $r_u = \frac{|g_{Sq}||g_{Su}|v_S^2}{m_u M_u} = (\frac{|g_{Sq}||g_{Su}|}{g_{Sl}^2})(\frac{m_D^2}{m_u M_u})$

  $r_d = \frac{|g_{Sq}||g_{Sd}|v_S^2}{m_d M_d} = (\frac{|g_{Sq}||g_{Sd}|}{g_{Sl}^2})(\frac{m_D^2}{m_d M_d})$

  $m_D = g_{Sl} v_S$: Dirac mass in seesaw.

  $m_\nu = m_D^2/M_R$
- Important remark: Even with maximal CP phases $\theta_q + \theta_{u,d} = \pi/2$, $\theta_{weak} \rightarrow 0$ if $r_{u,d} \rightarrow 0$.
- Assuming $g_{Sq}, g_{Su}, g_{Sd} \neq 0$, $\theta_{weak} \rightarrow 0$ if $v_S \rightarrow 0$ *or* $m_\nu \rightarrow 0$.
- Smallness of neutrino mass ⇒ smallness of $\bar{\theta}$! No need to make $\bar{\theta}$ zero.

Neutrinos and the strong CP problem

- Putting in numbers

$$\boxed{\theta_{Weak} < -10^{-8}\{(\frac{|g_{Sq}||g_{Su}|}{g_{Sl}^2})\sin(\theta_q+\theta_u) + (\frac{|g_{Sq}||g_{Sd}|}{g_{Sl}^2})\sin(\theta_q+\theta_d)\}}$$

- Without fine tuning, this implies $\boxed{|g_{Sq}| < |g_{Sl}| < 10^{-4}}$ ⇒ Displaced vertices for the mirror quarks too!
- How small would the neutron electric dipole moment be? It appears to be intrinsically tied to the absolute mass of the neutrinos!

Structure of Space-time at the Planck scale

- The Nielsen-Ninomiya no-go theorem stated that one cannot put the SM on the lattice since it requires fermions of opposite chiralities (mirror fermions) which interact with the same gauge bosons.
- The EW-ν_R model has such fermions. One can now put the EW-ν_R model on the lattice to study electroweak phase transition for example. If it were a mere calculational tool then it might not be quite satisfactory from a deep theoretical point of view.
- If however one boldly assumes that space is not continuous but discrete with a size of the order of the Planck scale then one cannot have the SM without mirror fermions!
- Several works on Quantum Gravity pointed to the need for discretized space. Above the Planck length ($\sim 10^{-35} m$), space appears to be continuous.

Conclusions

What does the EW-scale ν_R model accomplish?

- The EW-scale ν_R model provides a test of the seesaw mechanism at collider energies since ν_R's are now fertile and "light"! Rich studies involving the search for the mirror sector at the LHC with in particular characteristic signals such as $\boxed{\text{DISPLACED VERTICES}}$. Mirror fermions are $\boxed{\text{Long-Lived-Particles}}$!
- There seems to be a deep connection between $\boxed{\text{neutrino physics}}$ and $\boxed{\text{QCD}}$ in the solution to the strong CP problem.
- Nielsen-Ninomiya theorem: The EW-scale ν_R model evades the N-N theorem and one can now study EW phase transition on the lattice.
- If space is indeed discrete at the Planck scale then the Nielsen-Ninomiya no-go theorem requires the existence of mirror fermions. Deep implications for Quantum Gravity?

Some papers

- EW-scale nu_R model; PQH, Phys. Lett. B **649**, 275 (2007).
- EW precision: V. Hoang, P. Q. Hung and A. S. Kamat, Nucl. Phys. B **877**, 190 (2013) doi:10.1016/j.nuclphysb.2013.10.002 [arXiv:1303.0428 [hep-ph]].
- 125-GeV scalar: V. Hoang, P. Q. Hung and A. S. Kamat, Nucl. Phys. B **896**, 611 (2015) doi:10.1016/j.nuclphysb.2015.05.007 [arXiv:1412.0343 [hep-ph]].
- Rare decays: P. Q. Hung, T. Le, V. Q. Tran and T. C. Yuan, JHEP **1512**, 169 (2015) doi:10.1007/JHEP12(2015)169 [arXiv:1508.07016 [hep-ph]].

Some papers

- Searches: S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung and S. Nandi, Phys. Rev. D **93**, no. 3, 035007 (2016) doi:10.1103/PhysRevD.93.035007 [arXiv:1508.07318 [hep-ph]], S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung and S. Nandi, Phys. Rev. D **95**, no. 1, 015014 (2017) doi:10.1103/PhysRevD.95.015014 [arXiv:1606.08502 [hep-ph]].
- strong CP:arXiv:1704.06390 [hep-ph];mirror fermion searches:Phys. Lett. B **649**, 275 (2007); Phys. Rev. D **95**, no. 1, 015014 (2017);Phys. Rev. D **93**, no. 3, 035007 (2016),..
- More are in preparation.