A search for the first generation charged vector-like leptons at future colliders

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Abstract

Flavor Democracy Hypothesis favors existence of iso-singlet quarks and vector-like charged leptons. Their observation at future colliders could shed light on the nature of mass and mixing patterns of known leptons and quarks, as well as Higgs boson itself. Vector-like quarks are extensively searched by ATLAS and CMS collaborations. Unfortunately, this is not the case for vector-like leptons, while they have actually similar status from phenomenology viewpoint. We argue that vector-like charged leptons should be included into the new physics search programs of future energy frontier colliders. It is shown that pair production at the HE-LHC with decay of one of the leptons to \(Z\ell\) and another to \(H\ell\) channel, followed by \(H \rightarrow b\bar{b}\) and \(Z \rightarrow \mu^+\mu^-\) decays will give opportunity to scan masses of iso-singlet and iso-doublet charged leptons up to 0.9 TeV and 1.5 TeV, respectively. FCC will extend this region up to 2 TeV for iso-singlet and 3.6 TeV for iso-doublet charged leptons.

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1 Introduction

The verification of the basic elements of the Standard Model has been completed with the discovery of the Higgs boson in the LHC ATLAS and CMS experiments [1,2]. Nevertheless, there are a lot of problems which are not solved by the SM (see e.g. reviews [3,4] and references therein). Among them two most important ones, in our opinion, are: mass and mixing patterns of the SM fermions [5] in electroweak part and confinement [6] in QCD part. An essential stage in solving the first problem may be provided by the Flavor Democracy Hypothesis (see review [7] and references therein). The Confinement Hypothesis, in our opinion, will be clarified by future energy-frontier lepton-hadron colliders [8-14] rather than theoretically (lattice [15] etc.).
Flavor Democracy (FD) Hypothesis has a half-century history (for details see Section 2). Flavor Democracy in three SM family case was excluded by the large value of the top quark mass. In order to preserve FD in the SM framework existence of the fourth SM family (SM4) was proposed in 1990s. However, minimal SM4 with one Higgs doublet is excluded by experimental Higgs data. On the other hand, Flavor Democracy may be preserved with introduction of heavy vector-like quarks and leptons. Today vector-like quarks are extensively searched by ATLAS and CMS collaborations, but this is not the case for vector-like leptons (VLL).

In this paper potential of future energy-frontier colliders for search for first generation charged vector-like lepton has been estimated. In section 2 we present basics of Flavor Democracy Hypothesis and its relation to vector-like quarks and leptons. Decay modes and production cross-sections for iso-singlet and iso-doublet VLL’s are considered in section 3. Section 4 is devoted to search for pair produced charged VLL at future colliders, where \( L_e \to eZ/eH \) modes are considered with subsequent \( H \to bb \) and \( Z \to \mu^+\mu^- \) decays. Our conclusions and recommendations are given in section 5.

2 Flavor democracy calls for iso-singlet quarks and vector-like leptons

2.1 Weinberg’s statement

Mass and mixing patterns of the SM fermions are among the most important issues, which should be clarified in particle physics. In recent interview published in CERN Courier [5] Steven Weinberg emphasized this point: “Asked what single mystery, if he could choose, he would like to see solved in his lifetime, Weinberg doesn’t have to think for long: he wants to be able to explain the observed pattern of quark and lepton masses”. What Weinberg meant can be understood from Table 1, where current values of the SM charged leptons and quarks are presented. One can see that the top quark mass is of order of electroweak scale, whereas masses of remaining SM fermions are much smaller. In our opinion, Flavor Democracy (see reviews [3, 4, 7, 16–18] and references therein) could provide an important key to solve this mystery.

| Family | charged leptons | Up type quarks | Down type quarks |
|--------|-----------------|----------------|------------------|
| 1\(^{st}\) Family | 0.5109989461 ± 0.0000000031 MeV | 2.16\(^{+0.49}_{-0.26}\) MeV | 4.67\(^{+0.48}_{-0.17}\) MeV |
| 2\(^{nd}\) Family | 105.6583745 ± 0.0000024 MeV | 1.27 ± 0.02 GeV | 93\(^{+11}_{-5}\) MeV |
| 3\(^{rd}\) Family | 1776.86 ± 0.12 MeV | 172.76 ± 0.30 GeV | 4.18\(^{+0.03}_{-0.02}\) GeV |

2.2 Flavor Democracy

Flavor Democracy Hypothesis in framework of three family SM (SM3) was suggested in 1978 [19]. As mentioned in Introduction, Flavor Democracy in three SM family case was excluded by the large value of the top quark mass and in order to preserve FD in the SM framework existence of the fourth SM family (SM4) was proposed in 1990s [20–22]. However, minimal SM4 with one Higgs doublet is excluded by experimental Higgs data. On the other hand, Flavor Democracy may be preserved with introduction of heavy vector-like quarks and leptons [23]. In addition, FD has essential consequences if applied to MSSM and preonic models [7]. The next subsections (2.3-2.5) are based on reference [23].

2.3 Status of the Chiral Fourth Family

It is known that the Standard Model does not fix the number of fermion families. This number should be less than 9 in order to preserve asymptotic freedom and more than 2 in order to provide CP violation. According to the LEP data on Z decays, number of chiral families with light neutrinos \( (m_\nu << m_Z) \) is equal to 3, whereas extra families with heavy neutrinos are not forbidden. The fourth chiral family was widely discussed thirty years ago (see, for example [24,25]). However, the topic was pushed off the agenda due to the misinterpretation of the LEP data.
Twenty years later 3 workshops on the fourth SM family [26–28] were held (for summary of the first and third workshops see [29] and [30], respectively). Main motivation was Flavor Democracy [20–22], which naturally provides heavy fourth family fermions including neutrino (consequences of Flavor Democracy Hypothesis for different models, including MSSM and E6 inspired extension of the SM, have been considered in [7,31]). In addition, fourth family gives opportunity to explain baryon asymmetry of universe; it can accommodate emerging possible hints of new physics in rare decays of heavy mesons etc. (see [29] and references therein). Phenomenological papers on direct production (including anomalous resonant production) of the SM4 fermions at different colliders are reviewed in [32] (see tables VI and VII in [32]).

This activity has almost ended due to misinterpretation of the LHC data on the Higgs decays. It should be emphasized that these data exclude the minimal SM4 with one Higgs doublet, whereas non-minimal SM4 with extended Higgs sector is still allowed [33,34]. On the other hand, partial wave unitarity puts an upper limit around 700 GeV on the masses of fourth SM family quarks [35], which are excluded by the ATLAS and CMS data on search for pair u4 production [36,37].

Even if non-minimal SM4 may be excluded by the LHC soon, this is not the case for the general chiral fourth family (C4F). Therefore, ATLAS and CMS should continue a search for C4F up to kinematical limits. Concerning pair production, rescaling of the ATLAS lower bound using collider reach framework [38] shows that LHC will give opportunity to cover Mu4 up to 1.6 and 2.5 TeV with integrated luminosities 300 and 3000 fb−1, respectively. Resonant production of u4 via possible anomalous interactions may extend covered mass region up to 6 TeV [39].

2.4 Iso-singlet quarks

As mentioned in [3,4,7], large difference between \(m_t\) and \(m_b\) \((m_t >> m_b)\) can be explained by the existence of iso-singlet down quarks predicted by E6 GUT. Unlike this, the presence of vector-like up quarks predicted by Little Higgs models is useless, since it leads to \(m_b >> m_t\). Here we consider an addition of one iso-singlet down quark, so the quark sector is determined as

\[
\begin{pmatrix}
  u_L \\
  c_L \\
  t_L \\
  u_R, d_R, c_R, s_R, t_R, b_R, D_L, D_R
\end{pmatrix}
\]

where D denotes new iso-singlet quark.

In the case of full Flavor Democracy, the mass matrix of the up type quarks can be written as

\[
\begin{pmatrix}
  u_R & c_R & t_R \\
  u_L & \eta & \eta & \eta \\
  c_L & \eta & \eta & \eta \\
  t_L & \eta & \eta & \eta
\end{pmatrix}
\]

and mass matrix of down type quarks is

\[
\begin{pmatrix}
  d_R & s_R & b_R & D_R \\
  d_L & \eta & \eta & \eta & \eta \\
  s_L & \eta & \eta & \eta & \eta \\
  b_L & \eta & \eta & \eta & \eta \\
  D_L & M & M & M & M
\end{pmatrix}
\]

where \(M (M >> \eta)\) is the new physics scale that determines the mass of iso-singlet quark. Diagonalization of matrix 2 and 3 results in \(m_u = m_c = 0\) and \(m_t = 3\eta\) for up type quarks, \(m_d = m_b = m_s = 0\) and \(m_D = 3\eta + M = m_t + M\) for down type quarks.
In order to obtain mass of b quark, small deviation from matrix (3) is involved, namely

\[
\begin{array}{cccc}
  d_R & s_R & b_R & D_R \\
  d_L & a\eta & a\eta & (1 - \alpha_b)a\eta \\
  s_L & a\eta & a\eta & (1 - \alpha_b)a\eta \\
  b_L & a\eta & a\eta & (1 - \alpha_b)a\eta \\
  D_L & (1 - \beta_b)M & (1 - \beta_b)M & (1 - \beta_b)M & M \\
\end{array}
\]  

(4)

At this stage, for numerical calculations we assume \(\alpha_b = \beta_b \ll 1.\) While d and s quarks remain massless, we obtain following expressions for \(\alpha_b\) and \(m_D\)

\[\alpha_b = \frac{(m_t + M)m_b}{2m_t M} \]  

(5)

\[m_D \approx M + m_t - m_b \]  

(6)

i.e. \(\alpha_b \approx 1.31 \times 10^{-2}\) and \(m_D \approx 2169\) GeV if \(M = 2\) TeV. Because the masses of u and d quarks are very small, we do not comment on them at this stage. Masses of s and c quarks can also be obtained due to small deviations from full democracy. Concerning c quark let us consider following modification of the mass matrix of up quarks

\[
\begin{array}{cccc}
  u_R & c_R & t_R \\
  u_L & a\eta & a\eta & a\eta \\
  c_L & a\eta & a\eta & a\eta \\
  t_L & a\eta & a\eta & (1 + \alpha_c)a\eta \\
\end{array}
\]  

(7)

While u quark remains massless, we obtain following expressions for \(\alpha_c\)

\[\alpha_c = \frac{9m_c}{2m_t} = 3.3 \times 10^{-2} \]  

(8)

In order to obtain s quark mass, we consider following modification of the Eq. 4

\[
\begin{array}{cccc}
  d_R & s_R & b_R & D_R \\
  d_L & a\eta & a\eta & (1 - \alpha_b)a\eta \\
  s_L & a\eta & a\eta & (1 - \alpha_b)a\eta \\
  b_L & a\eta & a\eta & (1 - \alpha_b)a\eta \\
  D_L & (1 - \beta_b)M & (1 - \beta_b)M & (1 - \beta_b)M & M \\
\end{array}
\]  

(9)

For \(M = 2000\) GeV, \(\alpha_b = \beta_b = 1.32 \times 10^{-2}\) and \(\alpha_s = 2.48 \times 10^{-4}\) we obtain

\[m_D = 2168\] GeV, \(m_b = 4.18\) GeV, \(m_s = 95.2\) MeV  

(10)

Let us mention that down type iso-singlet quark give opportunity to explain \(4\sigma\) discrepancy in the first road of CKM matrix (see [10] and references therein).

Search for E6 iso-singlet quarks at the LHC was proposed in [11–44]. According to PDG [45] \(m_D > 1130\) GeV if \(B(D \to Z\bar{b}) = 1\) from CMS and \(m_D > 13500\) GeV if \(B(D \to Wt) = 1\) from ATLAS data.

2.5 Vector-like leptons

Similarly to b quark mass, low value of \(\tau\) lepton mass can be provided by adding an isosinglet charged lepton

\[
\left( \begin{array}{c}
  e_L \\
  \nu_e L \\
  \mu_L \\
  \nu_\mu L \\
  \tau_L \\
  \nu_\tau L \\
  e_R, \nu_e R, \mu_R, \nu_\mu R, \tau_R, \nu_\tau R, L_L, L_R
\end{array} \right)
\]  

(11)
Then, the mass matrix becomes as below

\[
\begin{array}{cccc}
\varepsilon_R & \mu_R & \tau_R & L_R \\
\varepsilon_L & \alpha \eta & \alpha \eta & \alpha \eta & (1 - \alpha \tau) \alpha \eta \\
\mu_L & \alpha \eta & \alpha \eta & \alpha \eta & (1 - \alpha \tau) \alpha \eta \\
\tau_L & \alpha \eta & \alpha \eta & \alpha \eta & (1 - \alpha \tau) \alpha \eta \\
L_L & (1 - \beta \tau) M & (1 - \beta \tau) M & (1 - \beta \tau) M & M \\
\end{array}
\] (12)

At this stage, for numerical calculations we assume \(\alpha \tau \ll 1\). While electron and muon remain massless, we obtain following expressions for \(\alpha \tau\) and \(m_L\)

\[
\alpha \tau = \frac{(m_t + M) m_\tau}{2 m_\nu M} \\
m_L \approx M + m_t - m_\tau 
\] (13) (14)

i.e. \(\alpha \tau \approx 6.02 \times 10^{-3}\) and \(m_L \approx 1171\) GeV if \(M = 1\) TeV.

In order to obtain muon mass, we consider following modification of the Eq. 12

\[
\begin{array}{cccc}
\varepsilon_R & \mu_R & \tau_R & L_R \\
\varepsilon_L & \alpha \eta & \alpha \eta & \alpha \eta & (1 - \alpha \tau) \alpha \eta \\
\mu_L & \alpha \eta & \alpha \eta & \alpha \eta & (1 - \alpha \tau) \alpha \eta \\
\tau_L & \alpha \eta & \alpha \eta & \alpha \eta & (1 + \alpha \mu) \alpha \eta & (1 - \alpha \tau) \alpha \eta \\
L_L & (1 - \beta \tau) M & (1 - \beta \tau) M & (1 - \beta \tau) M & M \\
\end{array}
\] (15)

For \(M = 2000\) GeV, \(\alpha \tau = \beta \tau = 5.58 \times 10^{-3}\) and \(\alpha \mu = 2.73 \times 10^{-4}\) this mass matrix lead to

\[
m_L = 2171\) GeV, \(m_\tau = 1.777\) GeV, \(m_\mu = 104.7\) MeV (16)

Concerning neutrinos, small value of their masses may be provided by see-saw mechanism. If neutrino masses have Dirac nature solution can be provided by addition of isosinglet heavy neutrino.

In fact, it seems more natural to add new particles for each family. For example, in the E6 model an iso-singlet quark and vector-like lepton iso-doublet are added for each SM family leading to \(6 \times 6\) mass matrices for down quarks (see [3, 4, 7]) and charged leptons. Therefore, it is quite possible that intra-family mixings between SM and VL leptons are dominant. So far we have considered minimal case, namely, one new down quark and one new charged lepton have been added.

3 Charged vector-like lepton decays and production

According to PDG [45] \(m_L > 100.8\) GeV if \(B(L \rightarrow W \nu) = 1\) from LEP data. Here we are concerned with iso-singlet leptons and E6 GUT predicted iso-doublet leptons (for most general case, namely, left-handed n-plet and right-handed m-plet see [44]). Below we assume that the mixing of the new lepton with the electron is dominant. The situation where the mixing with the muon is dominant will give similar results with the \(e - \mu\) exchange. The case in which the mixing with tau-lepton is dominant was examined in [46].

3.1 Charged vector-like lepton decays

In the iso-singlet case, there is one mixing angle \(\phi\) and 3 decay channels, namely, \(W \nu_e\), \(Ze\) and \(He\). Branching ratios to these channels are presented in Fig. 1 (left). Electroweak precision data leads to \(\sin \phi < 0.018\) [45]. In the iso-doublet case, we deal with two mixing angles: \(\phi_R\), which is responsible for \(Ze\) and \(He\) decays, and \(\phi_L\), which is responsible for \(W \nu_e\) decay. In Fig. 1 (right) neutral current (NC only) branching ratios are shown assuming \(\sin \phi_L = 0\). If \(\sin \phi_L \approx \sin \phi_R\) situation is similar to iso-singlet case presented in Fig. 1 (left).
Figure 1: Branching Ratios for decays of iso-singlet (left) and iso-doublet (right, NC only) charged vector-like lepton.

3.2 Charged vector-like lepton production

Cross-sections for pair production of charged vector-like leptons at the LHC, HE-LHC and FCC are shown in Fig. 2 and Fig. 3, respectively. It is seen that higher mass values for iso-doublet leptons comparing to iso-singlet ones can be probed at hadron colliders. As for lepton colliders, the area that can be scanned for iso-singlet and iso-doublet masses is the same (and close to kinematical limit, $\sqrt{s}/2$).

Figure 2: Cross-sections for pair production of charged vector-like leptons at the LHC and HE-LHC.
4 Estimations of observation limits for specific channel

Generally speaking we have 3 decay channels for new lepton following by a lot of decay channels for W, Z and H bosons. In our opinion most promising signature for hadron colliders will be provided by decay of one of the leptons to Ze and another to He channel, followed by $H \rightarrow bb$ and $Z \rightarrow \mu^+\mu^-$ decays. This decay chain gives opportunity to avoid complications coupled with missing energy, multi-lepton combinatorics and so on.

4.1 Hadron colliders

Cross-section for this channel is given by

$$
\sigma(pp \rightarrow e^+e^-\mu^+\mu^-bb + X) = 2 \times Br(L \rightarrow He) \times Br(L \rightarrow Ze) \times (Br(H \rightarrow bb) \times Br(Z \rightarrow \mu^+\mu^-) \times \sigma(pp \rightarrow L^+ L^- + X)
$$

(17)

According to the PDG $Br(H \rightarrow bb)=0.58$ and $Br(Z \rightarrow \mu^+\mu^-)=3.36 \times 10^{-2}$, $Br(L \rightarrow He)$ and $Br(L \rightarrow Ze)$ are presented in Fig. 1, $\sigma(pp \rightarrow L^+ L^- + X)$ is shown in Fig. 2 and Fig. 3. Assuming 25 events as observation limit for pair production at pp colliders we obtain achievable mass values at HL-LHC, HE-LHC and FCC presented in Table 2. As mentioned above in the case of iso-doublet leptons $E_R - e_R$ mixing results in $E \rightarrow eZ/eH$ decays proportional to $sin^2\phi_R$, whereas $E_L - e_L$ mixing leads to $E \rightarrow W\nu_e$ decays proportional to $sin^2\phi_L$. In Fig. 4 (left) we present observable mass limits at HE-LHC for general case where vertical axis shows $BR(E \rightarrow eZ) = BR(E \rightarrow eH)$ values. $BR(E \rightarrow eZ) = BR(E \rightarrow eH) = 0.5$ corresponds to $sin^2\phi_L = 0$. Similar graphic for FCC is also shown in Fig. 4 (right).

| $\mathcal{L}[fb^{-1}]$ | HL-LHC | HE-LHC | FCC |
|--------------------------|--------|--------|-----|
|                          | 1000   | 3000   | 1000| 10000 | 10000 | 2000 |
| Isosinglet M [GeV]       | 340    | 460    | 490 | 910   | 845   | 2025 |
| Isodoublet M [GeV]       | 610    | 775    | 900 | 1530  | 1645  | 3650 |

Let us emphasize that these results are applicable for second generation charged VLL if $L_\mu \rightarrow \mu Z/\mu H$ modes are considered with subsequent $H \rightarrow bb$ and $Z \rightarrow e^+e^-$ decays.
4.2 Lepton colliders

At lepton colliders masses of iso-singlet and iso-doublet charged VLL can be scanned up to values close to kinematical limit, $\sqrt{s}/2$. Concerning signature under consideration ILC with $\sqrt{s} = 1$ TeV is comparable with the HL-LHC for isosinglet charged leptons, CLIC or Muon Collider (MC) with $\sqrt{s} = 3$ TeV potential exceeds that of HL-LHC both for isosinglet and isodoublet and HE-LHC for isosinglet charged leptons, MC with $\sqrt{s} = 6$ TeV potential exceeds that of HE-LHC both for isosinglet and isodoublet and FCC for isosinglet charged leptons.

5 Conclusion

From phenomenology viewpoint vector-like leptons have the same status vector-like quarks and should be included into the new physics search programs of energy frontier colliders. Existence of iso-singlet quarks and vector-like charged leptons is favored by Flavor Democracy Hypothesis, which could provide an important key to solve the mystery of mass and mixing patterns of the SM fermions. We argued that most promising signature for pair production of first family vector-like lepton at hadron colliders will be provided by decay of one of the leptons to $Ze$ and another to $He$ channel, followed by $H \rightarrow bb$ and $Z \rightarrow \mu^+\mu^-$ decays. Summary of our results are presented in Table 2 and Figure 4. For example, HL-LHC will cover mass range up to 460 GeV for iso-singlet and 775 GeV for iso-doublet VL charged leptons. FCC could extend these ranges up to 2 TeV and 3.6 TeV, respectively. Mass limits given above are results of rough estimations. Detailed simulations should be made for more realistic values. We assume that the discovery limits for pp colliders would be higher if other decay channels were also included in the analysis. Corresponding studies continue in this context.
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