Saving fourth generation and baryon number by living long

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Recent studies of precision electroweak observables have led to the conclusion that a fourth generation is highly constrained. However, we point out that a long-lived fourth generation can reopen a large portion of the parameter space. In addition, it preserves baryon and lepton asymmetries against sphaleron erasure even if $B - L = 0$. It opens up the possibility of exact $B - L$ symmetry and hence Dirac neutrinos. The fourth generation can be observed at the LHC with unique signatures of long-lived particles in the near future.

When the muon was discovered as an exact copy of the electron but with a higher mass, people wondered why nature repeats in an apparently unnecessary fashion. Later, discovery of CP violation led Kobayashi and Maskawa to predict that nature actually repeats itself at least three times. There is no obvious reason why it should stop with three. At the same time, CP violation also led Sakharov to consider how the apparent lack of anti-matter in the universe might be explained. Therefore the apparent repetition of generations of elementary particles has an intimate connection with the issue of baryogenesis.

The fourth generation (4G) is indeed the simplest extension of the standard model being searched for at Tevatron and at the LHC. However, several groups have claimed recently that this simple extension of the standard model (SM) is highly constrained [1-3] or already ruled out with no (CKM) mixing to the SM [4] by a combination of collider searches for its direct production and its indirect effects in Higgs boson production, together with the precision electroweak observables.

In this letter, we consider a long-lived 4G due to extremely small mixings between the fourth and lighter three generations. It could be a consequence of a flavor symmetry or flavor asymmetries against sphaleron erasure even if $B - L = 0$. It opens up the possibility of exact $B - L$ symmetry and hence Dirac neutrinos. The fourth generation can be observed at the LHC with unique signatures of long-lived particles in the near future.

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only calculated at the tree level and hence the bound is soft.

The allowed mass region for the fourth-generation quarks is presented in Fig. 1. Firstly and most importantly, we find a large allowed region for $m_U \lesssim m_D$ as opposed to previous analyses which assumed $m_{E,N} \gtrsim 100$ GeV, whose contribution to the $S$ parameter is positive together with the Higgs contribution. Then the $S$-parameter constraint only allows a small mass region for $m_U > m_D$. However, for a light fourth-generation neutrino (around 46 GeV), the fourth-generation lepton contribution to the $S$ parameter is negative (around $-0.09$). Hence, large fourth-generation quark masses ($m_U \lesssim m_D$) with a relatively large $S$ parameter are allowed. Secondly, varying $m_E$ does not change the allowed parameter space because decreasing $m_N$ can compensate for the $S$, $T$ contribution from increasing the Higgs mass.

In Ref. [4], it is claimed that the 4G with small mixing is ruled out by the a combination of EWPTs, direct searches and the indirect bounds from the Higgs production at Tevatron. We will explain our disagreement with the author. The author first fixes $m_U - m_D = 16$ GeV and $m_E - m_N = 91$ GeV [1] which is a very limited region of the allowed parameter space which is clear from our Fig. 1. Then he finds the Higgs mass required by EWPTs in the zero mixing case for the two end point mass of $m_U$ and $m_D$ in the line $m_U - m_D = 16$ GeV is ruled out by the direct Tevatron Higgs boson search. However, the mixing between 3rd and 4th generation increases the $T$ parameter only (see formula one in Ref. [4]), effectively the same as increasing the $U$ and $D$ mass splitting [29].

Havening demonstrated that longevity makes the 4G phenomenologically viable, we now turn our attention to the baryon asymmetry. In the SM, $B$ and $L$ are separately conserved except for the sphaleron transitions [15] which violate $B + L$ but preserve $B - L$. The net $B$ must be proportional to the only conserved quantity $B - L$ and would be zero if $B - L = 0$. After the the sphaleron transitions get decoupled from thermal equilibrium at $T_{\text{sp}}$, $B$ is a conserved quantity which gives us the right number density today.

If the 4G fermions do not mix with the lighter generations significantly, they would stay in chemical equilibrium only through the electroweak sphaleron transitions, which maximally violate $3B + 3L + B_4 + L_4$ instead. Here we use $B$ or $L$ as the baryon or lepton number in the first three generations. In this case, the other three orthogonal combinations of $B$, $L$, $B_4$, $L_4$ are conserved charges. The final $B$ is a linear combination of these conserved charges instead of just being proportional to $B - L$. As a consequence, unless there exists some accidental cancellations, the net baryon number density would be nonzero even if $B - L = 0$.

The thermal history for baryon number generation after inflation is summarized as follows. First, we assume there is some baryogenesis mechanism which generates a net baryon asymmetry $B + B_4 = L + L_4 \neq 0$. However, this initial condition could generate an asymmetry in the other conserved charges (for instance, $L - 3L_4$). Above the critical temperature $T_\text{c}$ of the electroweak phase transition, all particles are massless and net $B$ could be small or zero depending on the particle content of the model. Below $T_\text{c}$, all fermions gain their masses via the Higgs mechanism, so it costs additional energy to create the heavy fourth generation fermions. Once the temperature drops below their masses, the mass effect essentially blocks the sphaleron process from erasing $B$ [30].

We follow the standard analysis in Ref. [16] while taking into account all the mass effects. We choose a single chemical potential $\mu$ for leptons instead of separate chemical potentials for each light lepton flavor as in Refs. [17–20]. We consider the SM matter consisting of three families, each of which consists of two quarks (an up-type and down-type) with masses $m_{q_1}$, a charged lepton of mass $m_{l_1}$ and a massless neutrino. The SM interactions relate all the chemical potentials which leave us with six independent chemical potentials in our case: $\mu_{u_1}$, $\mu_{W}$, $\mu_0$, $\mu_{U_1}$, $\mu_{N_1}$, $\mu = \sum_i \mu_i = 3 \mu_{\nu L}$ which are the chemical potentials for upper type quarks, $W^-$ bosons, neutral Higgs boson, 4G up type quark, 4G neutrino, sum over all SM neutrino chemical potentials.

$$
\mu_{d_L} = \mu_{u_L} + \mu_W \quad (W^- \leftrightarrow \bar{u}_L + \bar{d}_L)
$$
$$
\mu_{D_L} = \mu_{U_L} + \mu_W \quad (W^- \leftrightarrow \bar{U}_L + \bar{D}_L)
$$
$$
\mu_{e_L} = \mu_{\nu L} + \mu_W \quad (W^- \leftrightarrow \bar{\nu}_L + e_L)
$$
$$
\mu_{E_L} = \mu_{N_1} + \mu_W \quad (W^- \leftrightarrow \bar{N}_L + E_L)
$$
$$
\mu_{u_R} = \mu_0 + \mu_{u_L} \quad (\phi^0 \leftrightarrow \bar{u}_L + u_R)
$$

FIG. 1: The $m_D$ vs $m_U$ contour plot for varying fourth-generation lepton masses. The purple region is the allowed mass region from the $S$-$T$ constraint at 95% C.L. for $m_h = 130$ GeV and the blue region (including the purple region) is that for $m_h = 300$ GeV. The lower limit of the green region comes from the direct searches at the Tevatron (The solid line is the case for long-lived fourth-generation quarks and the dashed line is the case for the prompt decay), while the upper limit is the bound from unitarity. The purple and the blue lines use the approximate formula for the fourth generation quark masses $m_U - m_D = (1 + \frac{1}{2} \log(\frac{m_{4G}}{m_{3G}})) \times 50$ GeV from Ref. [5] for $m_h = 130$ GeV and 300 GeV, respectively.
The electroweak sphaleron process which converts charge densities are

where the net mass function in Eq. (3) for mass correction functions for bosons and fermions are normalized as \( \alpha_b(0) = \alpha_f(0) = 1 \). We define \( \Delta \equiv N - \sum_i \alpha_i \) (\( N = 3 \)) for SM particles with \( i = 1, 2, 3 \) generations. \( \Delta_u, \Delta_d, \Delta_s, \Delta_e \) stands for the overall mass corrections for up type SM quarks, down type SM quarks and SM charged leptons, respectively. The \( \alpha_V, \alpha_u, \alpha_d, \alpha_D, \alpha_E \) and \( \alpha_N \) are the mass function in Eq. (3) for W boson, neutral Higgs, 4G up-quark, 4G-down quark, 4G charged lepton and 4G neutrino respectively. It is easy to see \( \Delta_\downarrow \) and \( \Delta_\uparrow < 5 \times 10^{-4} \) since \( T_{sph} > m_W \) so we will ignore their contribution in the following discussions. The neutral Higgs bosons condense so we have \( \mu_0 = 0 \). One can write the charge densities in terms of the chemical potential (upto irrelevant constants):

\[
Q \approx 2(N - 2\Delta_u)\mu_{uL} - 2(2N + 3\alpha_W)\mu_W - 2\mu + 4\alpha_U\mu_{UL} - 2\alpha_D(\mu_{UL} + \mu_W) - 2\alpha_E(\mu_{NL} + \mu_W)
\]

\[
B \approx (4N - 2\Delta_u)\mu_{uL} + 2N\mu_W
\]

\[
L \approx 3\mu + 2N\mu_W
\]

\[
B_4 = 2\alpha_U\mu_{UL} + 2\alpha_D(\mu_{UL} + \mu_W)
\]

\[
L_4 = 2\alpha_N\mu_{NL} + 2\alpha_E(\mu_{NL} + \mu_W),
\]

where the net \( Q \) (electric charge density) must be 0. The conserved charge densities are

\[
B - L = (4N - 2\Delta_u)\mu_{uL} - 3\mu
\]

\[
B_4 - L_4 = 2\alpha_U\mu_{UL} + 2\alpha_D(\mu_{UL} + \mu_W) - 2\alpha_N\mu_{NL} - 2\alpha_E(\mu_{NL} + \mu_W)
\]

\[
L - 3L_4 = 3\mu + 2N\mu_W - 6\alpha_N\mu_{NL} - 6\alpha_E(\mu_{NL} + \mu_W).
\]

The electroweak sphaleron process which converts \( qqlq \) of each generation into nothing give us the last constraint

\[
3N\mu_{uL} + 2(N + 1)\mu_W + \mu + 3\mu_{UL} + \mu_{NL} = 0.
\]
the allowed window for the proper lifetime is $10^{-10}\,\text{s} < \tau_0 < 1\,\text{s}$, which also corresponds to the small mixing angle $10^{-13} < \theta < 10^{-8}$. Their decay length at the LHC is $d = \beta c r \gamma \approx (30\,\text{mm}) \left(\tau/10^{-10}\,\text{s}\right) \beta r$. If the lifetime is relatively short within the above range, the 4G quarks show displaced vertices in their decays. On the other hand, if the 4G quarks decay outside the detector, the lighter 4G quark would hadronize and the signal would look like a jet with tracks, with anomalously large energy deposits in the silicon detector or delayed hits in the calorimeters or muon chamber. At the early LHC, this is one of the signals that can be looked for. At the same time, it may cause confusion if the charge-exchange reaction with the detector material causes the charged bound state to turn neutral and vice versa, making the track a “dashed line” [28].

Unfortunately, we are not aware of any ATLAS/CMS simulation on the long-lived 4G quarks. However, we can rescale the production rate and use the study for the long-lived stop at the early LHC. The work is partially supported by the World Premier International Research Center Initiative (WPI initiative) MEXT, Japan. H.M. was also supported in part by the U.S. DOE under Contract DE-AC03-76SF00098, in part by the NSF under grant PHY-04-57315, and in part by the Grant-in-Aid for scientific research (C) 20540257 from Japan Society for Promotion of Science (JSPS). J.S. is also supported by the Grant-in-Aid for scientific research (Young Scientists (B) 21740169) from JSPS.

Table I: The required integrated luminosity $\mathcal{L}_{\text{int}}$ for LHC $\sqrt{s} = 14\,\text{TeV}$ to observe 3 events for the long-lived stop production for their different masses. The data are quoted from Fig. 2 (left) in Ref. [26].

| $\mathcal{L}_{\text{int}}$ (pb$^{-1}$) | 0.2 | 1 | 4 | 20 | 40 | 100 |
|-----------------------------|-----|---|---|----|----|-----|
| $m$ (GeV)                  | 200 | 300 | 400 | 500 | 600 | 700 |

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[30] There are related scenarios which generates the dark matter abundance through sphalerons [22], preserves $B$ relying on $\tau$ lepton mass [19] or Dirac neutrino mass [27].
[31] The estimation of the proper lifetime and traveling distance also applies to the forth generation quarks, and the lightest fourth generation neutrino will look like missing energy.