Heavy Majorana neutrino pair productions at the LHC in minimal $U(1)$ extended Standard Model

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Based on: Phys. Rev. D 97, no. 11, 115023 (2018) and Eur. Phys. J. C 78, no.9, 696 (2018).

Abstract Towards experimental confirmations of the type-I seesaw mechanism, we explore a prospect of discovering the heavy Majorana right-handed neutrinos (RHNs) from a resonant production of a new massive gauge boson (Z') and its subsequent decay into a pair of RHNs ($Z' \to NN$) at the High Luminosity Large Hadron Collider (HL-LHC). Recent simulation studies have shown that the discovery of the RHNs through this process is promising in the future. However, the current LHC data very severely constrains the production cross section of the Z' boson into a dilepton final states, ($pp \to Z' \to \ell^+\ell^-,\ \ell = e/\mu$). Extrapolating the current bound to the future, we find that a significant enhancement of the branching ratio BR($Z' \to NN$) over BR($Z' \to \ell^+\ell^-$) is necessary for the future discovery of RHNs. As a well-motivated simple extension of the standard model (SM) to incorporate the Z' boson and the type-I seesaw mechanism, we consider the minimal $U(1)_X$ model. We point out that this model can yield a significant enhancement up to BR($Z' \to NN$)/BR($Z' \to \ell^+\ell^-$) $\simeq 5$ (per generation).With such an enhancement and a realistic model-parameter choice to reproduce the neutrino oscillation data, we conclude that the possibility of discovering RHNs with, for example, a 3000 fb^{-1} luminosity implies that the Z' boson will be discovered with a luminosity of 853 fb^{-1} (626 fb^{-1}) for the normal (inverted) hierarchy of the light neutrino mass pattern.

Introduction

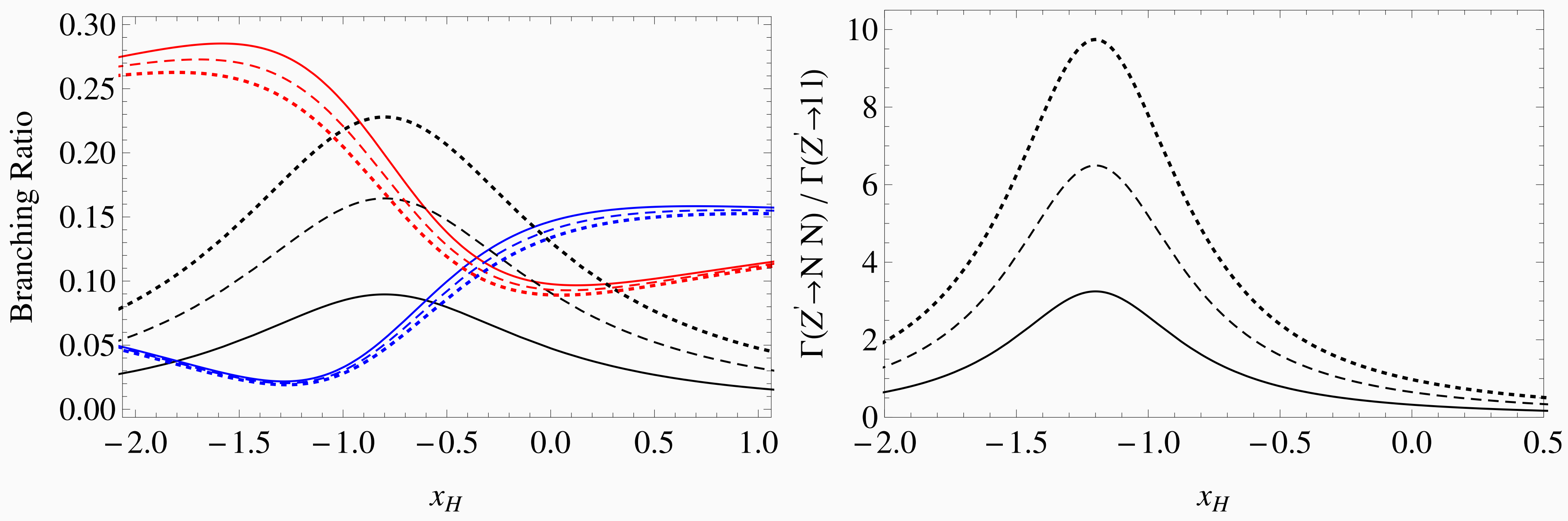
- Existence of the tiny neutrino mass and the flavor mixing has already been established by the neutrino oscillation experiments.
- Such a result can not be explained by the existing Standard Model (SM) of particle physics which leads us to an immediate extension of it.
- Among many choices, seesaw mechanism is the simplest idea which was originated from the dimension 5 operator between the SM lepton doublets and SM Higgs doublet. Such an operator violates the lepton number by $\Delta L = 2$ units. After the EWSB the neutrinos acquire the tiny Majorana masses suppressed by the scale of the dimension 5 operator.
- In the context of a renormalizable theory, the dimension-5 operator is naturally generated by introducing heavy Majorana right-handed neutrinos (RHNs), which are singlet under the SM gauge group, and integrating them out. This is the so-called type-I seesaw mechanism
- If the RHNs have masses around 1 TeV or smaller, they can be produced at the Large Hadron Collider (LHC) with a smoking-gun signature of a same-sign dilepton in the final state, which indicates a violation of the lepton number. Since the RHNs are singlet under the SM gauge group, they can be produced only through their mixings with the SM neutrinos.

Seesaw scenario in the $U(1)_X$ extended SM

- Particle content under the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$:
  $q_L^i = \{\mathbf{3},\ \mathbf{2},\ \mathbf{1/6},\ \mathbf{(1/6)x_H + (1/3)x_\Phi}\}$
  $u_R^i = \{\mathbf{3},\ \mathbf{1},\ \mathbf{2/3},\ \mathbf{(2/3)x_H + (1/3)x_\Phi}\}$
  $d_R^i = \{\mathbf{3},\ \mathbf{1},\ \mathbf{-1/3},\ \mathbf{-(1/3)x_H + (1/3)x_\Phi}\}$
  $\ell_L^i = \{\mathbf{1}, \mathbf{2}, \mathbf{-1/2}, \mathbf{(-1/2)x_H - x_\Phi}\}$
  $e_R^i = \{\mathbf{1}, \mathbf{1}, \mathbf{-1}, \mathbf{-x_H - x_\Phi}\}$
  $H = \{\mathbf{1}, \mathbf{2}, \mathbf{-1/2}, \mathbf{(-1/2)x_H}\}$
  $N_R^j = \{\mathbf{1}, \mathbf{1}, \mathbf{0}, \mathbf{-x_\Phi}\}$
  $\Phi = \{\mathbf{1}, \mathbf{1}, \mathbf{0}, \mathbf{+2x_\Phi}\}$

- Particle content of the minimal $U(1)_X$ model, where $i, j = 1, 2, 3$ are the generation indices. Without loss of generality, we fix $x_\Phi = 1$.
- Yukawa Interaction : $\mathcal{L}_Y \supset -\sum_{i,j=1}^3 Y_D^{ij} \overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{i=k}^3 Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \text{h.c.}$, where the first and second terms are the Dirac and Majorana Yukawa couplings. Here we use a diagonal basis for the Majorana Yukawa coupling without loss of generality.
- After the U(1)$_X$ and the EW symmetry breakings, U(1)$_X$ gauge boson mass, the Majorana masses for the RHNs, and neutrino Dirac masses are generated: $m_{Z'} = g_X\sqrt{4v_\Phi^2 + \frac{1}{4}x_H^2 v_h^2} \simeq 2g_X v_\Phi$, $m_{N^i} = \frac{Y_N^i}{\sqrt{2}}v_\Phi$, $m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}}v_h$ where g_X is the U(1)$_X$ gauge coupling, v_Φ is the Φ VEV, $v_h = 246$ GeV is the SM Higgs VEV, and we have used the LEP constraint [hep-ph/0408098,arXiv:1408.6845] ${v_\Phi}^2 \gg {v_h}^2$.
- $\Gamma(Z' \to \overline{f_L} f_L) = N_c \frac{g_X^2}{24\pi} Q_{f_L}^2 m_{Z'}$ $\Gamma(Z' \to N^i N^i) = \frac{g^2}{24\pi} m_{Z'}\left(1 - \frac{4m_{N^i}^2}{m_{Z'}^2}\right)^{3/2}$ $N_c = 1(3)$ for leptons (quarks), Q_{f_L} is the U(1)$_X$ charge of the SM fermion, and we have neglected all the SM fermion masses. we show the Z' boson branching ratios for $m_{Z'} = 3$ TeV. The solid lines correspond to $m_{N^1} = m_{Z'}/4$ and $m_{N^{2,3}} > m_{Z'}/2$, the dashed (dotted) lines correspond to $m_{N^{1,2}} = m_{Z'}/4$ and $m_{N^3} > m_{Z'}/2$ ($m_{N^{1,2,3}} = m_{Z'}/4$).
- For the SM final states, we show branching ratios to only the first generation dilepton and jets (sum of the jets from up and down quarks). The lines for the RHN final states correspond to the sum of the branching ratio to all possible RHNs. The plot shows the enhancement of RHNs branching ratios around $x_H = -0.8$ with the maximum values of the branching ratios, 0.09, 0.16, and 0.23 for the cases with one, two, and three generations of RHNs, respectively.
- $\frac{\Gamma(Z' \to NN)}{\Gamma(Z' \to \ell^+\ell^-)} = \frac{4}{8 + 12x_H + 5x_H^2}\left(1 - \frac{4m_N^2}{m_{Z'}^2}\right)^{\frac{3}{2}}$.

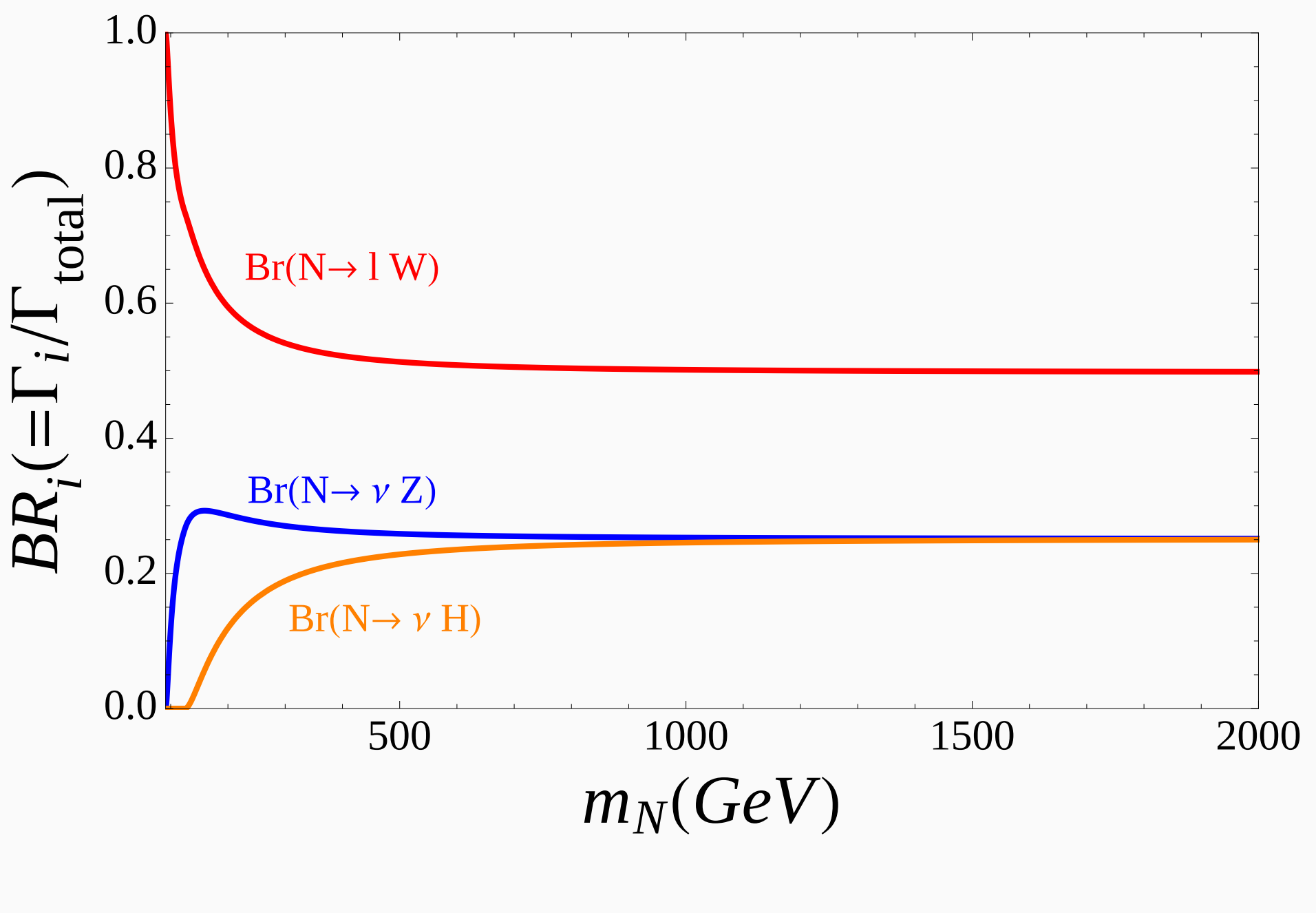
Z' decays



(Left)For the minimal U(1)$_X$ model, the plot shows the branching ratios of Z' as a function of x_H with a fixed $m_{Z'} = 3$ TeV. The solid lines correspond to $m_{N^1} = m_{Z'}/4$ and $m_{N^{2,3}} > m_{Z'}/2$; the dashed (dotted) lines correspond to $m_{N^{1,2}} = m_{Z'}/4$ and $m_{N^3} > m_{Z'}/2$ ($m_{N^{1,2,3}} = m_{Z'}/4$). From top to bottom, the solid (red, black and blue) lines at $x_H = -1$ are the branching ratios to the first generations of jets (up and down quarks), RHNs , and charged leptons, respectively. The lines for the RHN final states correspond to the sum of the branching ratio to all possible RHNs. (Right) The ratio of the partial decay widths of Z' boson into RHNs and dilepton final states as a function of x_H. The solid line corresponds to $m_{N^1} = m_{Z'}/4$ and $m_{N^{2,3}} > m_{Z'}/2$; the dashed (dotted) lines correspond to $m_{N^{1,2}} = m_{Z'}/4$ and $m_{N^3} > m_{Z'}/2$ ($m_{N^{1,2,3}} = m_{Z'}/4$). We find the peaks at $x_H = -1.2$ with the maximum values of 3.25, 6.50, and 9.75, respectively. We focus on the same sign dimuon and diboson final state as a smoking gun scenario of Majorana RHNs.

Right Handed Neutrinos

Assuming the hierarchy of $|m_D^{ij}/M_N| \ll 1$, we have the seesaw formula for the light Majorana neutrinos as $m_\nu \simeq -\frac{1}{M_N} m_D m_D^T$, where $M_N = m_{N^1} = m_{N^2} = m_{N^3}$. We express the light neutrino flavor eigenstate (ν) in terms of the mass eigenstates of the light (ν_m) and heavy (N_m) Majorana neutrinos such as $\nu \simeq U_{\rm MNS}\ \nu_m + \mathcal{R}\ N_m$, where $\mathcal{R} = m_D/M_N$, and $U_{\rm MNS}$ is the neutrino mixing matrix by which m_ν is diagonalized as $U_{\rm MNS}^T m_\nu U_{\rm MNS} = D_\nu = {\rm diag}(m_1, m_2, m_3)$. The heavy neutrino mass eigenstates have the charged current, the neutral current, and the Yukawa interactions as follows: $\mathcal{L}_{int} \supset -\frac{g}{\sqrt{2}} W_\mu^+ \overline{\ell_\alpha}\gamma^\mu P_L \mathcal{R}_{\alpha j} N_m^j - \frac{g}{2\cos\theta_{\rm W}} Z_\mu \overline{\nu_\alpha}\gamma^\mu P_L \mathcal{R}_{\alpha j} N_m^j - \frac{1}{\sqrt{2}v_h} h\overline{\nu_\alpha} P_L \mathcal{R}_{\alpha j} N_m^j$ where ℓ_α and ν_α ($\alpha = e, \mu, \tau$) are the three generations of the charged leptons and neutrinos, $P_L = (1-\gamma_5)/2$, and $\theta_{\rm W}$ is the weak mixing angle. Through the above interactions, a heavy neutrino mass eigenstate N_m^i ($i = 1, 2, 3$) decays into $\ell_\alpha W$, $\nu_\alpha Z$, and $\nu_\alpha h$. The corresponding branching rations are given in the figure as:



Conclusion

- Generalizing the Dirac mass matrix $m_D = \sqrt{M_N} U_{\rm MNS}^* \sqrt{D_\nu} O$, where $\sqrt{D_\nu} = diag(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$ and O is a general 3×3 complex orthogonal matrix, with neutrino oscillation data, $M_N = \frac{M_Z'}{4}$, $M_Z' = 3$ TeV, we find the maximum value of $\Sigma_{i=1}^3 BR(NN \to \mu^\pm\mu^\pm W^\mp W^\mp)$ will be $0.210(0.154)$ for the normal (inverted) hierarchy taking lightest neutrino mass eigenvalue as $m_{\rm lightest} = 0.1 \times \sqrt{\Delta m_{12}^2}$ and real parameter choice of O.
- We have shown that this model can yield the significant enhancement of $\frac{{\rm BR}(Z' \to NN)}{{\rm BR}(Z' \to \ell^+\ell^-)} \simeq 3.25$ (per generation) for $x_H = -1.2$, with $m_{Z'} = 3$ TeV and $m_N = m_{Z'}/4$ therefore $\sigma(pp \to Z' \to NN \to \mu^\pm\mu^\pm W^\mp W^\mp) \simeq 0.02$ fb for the 5-σ discovery of the RHN with a 3000 fb^{-1} luminosity [JHEP 01 (2018) 037] when Z' can be discovered at 853 (626) fb^{-1} luminosity for the normal (inverted) hierarchical light neutrino mass pattern.