

# Standard-model-like Higgs boson production at the CERN LHC in 3-3-1 model with right-handed neutrinos

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The models based on  $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$  gauge group (3-3-1) contain new Higgs bosons and one of them is the SM-like Higgs boson  $h$ . Production of this Higgs boson at  $pp$  colliders in the framework of 3-3-1 model with right-handed neutrinos is calculated. We found that the contribution of the real  $Z'$  to the process  $pp \rightarrow hZ$  is nearly 60 fb if  $M_{Z'}$  is about 1 TeV. The decay width and the branching ratios of the  $Z'$  extra neutral gauge boson are systematically discussed.

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## I. INTRODUCTION

The recent experimental results of SuperKamiokande Collaboration [1], KamLAND [2] and SNO [3] confirm that neutrinos have *tiny* masses and oscillates. This implies that the standard model (SM) must be extended.

Among the possible extensions of SM, a curious choice is the 3-3-1 models which are based on the simplest non-Abelian extension of the SM group, namely, the  $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$  [4, 5]. The reason why these models are appealing have been exposed in many recent publications [6]. The model requires that the number of fermion families be a multiple of the quark color in order to cancel anomalies, which suggests an interesting connection between the number of flavors and the strong color group. If further one uses the condition of QCD asymptotic freedom, which is valid only if the number of families of quarks is to be less than five, it follows that  $N$  is equal to 3. In addition, the third quark generation has to be different from the first two, so this leads to the possible explanation of why top quark is uncharacteristically heavy.

There are two main versions of the 3-3-1 models as far as lepton sector is concern. In the minimal version, the charge conjugation of the right-handed charged lepton for each generation is combined with the usual  $SU(2)_L$  doublet left-handed leptons components to form an  $SU(3)$  triplet  $(\nu, l, l^c)_L$ . No extra leptons are needed and there we shall call such models minimal 3-3-1 models. There is no right-handed (RH) neutrino in its minimal version. Another version adds a left-hand anti-neutrino to each usual  $SU(2)_L$  doublet left-handed lepton to form a triplet. This model is called the 3-3-1 model with RH neutrinos.

It is well known that the electroweak symmetry break-

ing in the SM is achieved via the Higgs mechanism. In the Glashow-Weinberg-Salam model there are a single complex Higgs doublet, where the Higgs boson  $h$  is the physical neutral Higgs scalar which is the only remaining part of this doublet after spontaneous symmetry breaking. In the extended models there are additional charged and neutral scalar Higgs particles. The search for the Higgs boson is an important part of the Fermilab Tevatron experiments and will be one of the main fields of study at the CERN LHC collider. The experimental detection of the  $h$  will be great triumph of the SM of electroweak interactions and will mark new stage in high energy physics.

Production of the Higgs boson in the minimal 3-3-1 model at the  $e^-e^+$  Next Linear Collider and in CERN Linear Collider (CLIC) has been considered in [7]. The aim in this paper is to consider production of the Higgs boson of the SM at hadron colliders.

The rest of the paper is organized as follows: In Sec. 2 a brief review of the 3-3-1 model with RH neutrinos is presented. Sec. 3 is devoted to the decay of the  $Z'$  extra gauge bosons. In Sec. 4 we discuss single production of the  $Z'$  and the SM Higgs bosons. Finally, our conclusions are presented in Sec. 4.

## II. A REVIEW OF 3-3-1 MODEL WITH RH NEUTRINOS

The 3-3-1 model is based on the gauge group

$$SU(3)_C \otimes SU(3)_L \otimes U(1)_X. \quad (1)$$

In the version considered in this paper, one adds a left-hand anti-neutrino to each usual  $SU(2)_L$  doublet left-handed lepton to form a triplet [5]

$$f_L^a = \begin{pmatrix} \nu_L^a \\ e_L^a \\ (\nu_L^c)^a \end{pmatrix} \sim (1, 3, -1/3), e_R^a \sim (1, 1, -1), \quad (2)$$

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where  $a = 1, 2, 3$  is the generation index. Two first quark generations belong to antitriplets and the third is in triplet

$$Q_{iL} = \begin{pmatrix} d_{iL} \\ -u_{iL} \\ D_{iL} \end{pmatrix} \sim (3, 3^*, 0), \quad (3)$$

$$u_{iR} \sim (3, 1, 2/3), d_{iR} \sim (3, 1, -1/3), \\ D_{iR} \sim (3, 1, -1/3), \quad i = 1, 2,$$

$$Q_{3L} = \begin{pmatrix} u_{3L} \\ d_{3L} \\ T_L \end{pmatrix} \sim (3, 3, 1/3), \quad (4)$$

$$u_{3R} \sim (3, 1, 2/3), d_{3R} \sim (3, 1, -1/3), T_R \sim (3, 1, 2/3).$$

The electric charge operator is defined as

$$Q = \frac{1}{2}\lambda_3 - \frac{1}{2\sqrt{3}}\lambda_8 + X. \quad (5)$$

From 5) we get the electric charge of the new exotic quarks to be  $-\frac{1}{3}$  and  $\frac{2}{3}$  as in (3) and (4).

The gauge symmetry breaking and fermion mass generation can be achieved with just three  $SU(3)_L$  triplets

$$\eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta'^0 \end{pmatrix} \sim (1, 3, -1/3), \quad (6)$$

$$\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho'^+ \end{pmatrix} \sim (1, 3, 2/3), \quad (7)$$

$$\chi = \begin{pmatrix} \chi^0 \\ \chi^- \\ \chi'^0 \end{pmatrix} \sim (1, 3, -1/3), \quad (8)$$

with the following VEVs

$$\langle \eta \rangle^T = (v, 0, 0), \langle \rho \rangle^T = (0, u, 0), \langle \chi \rangle^T = (0, 0, w). \quad (9)$$

Note that the scalars  $\eta$  and  $\chi$  have the same quantum numbers.

To be consistent with low energy phenomenology, we have to impose the following condition

$$w \gg v, u. \quad (10)$$

The neutral gauge boson  $Z$  and the new neutral  $Z'$  interact with fermions as follows

$$\begin{aligned} \mathcal{L}^{NC} &= \frac{g}{c_W} \left\{ \bar{f} \gamma^\mu \left[ a_{1L}(f) \frac{1-\gamma_5}{2} + a_{1R}(f) \frac{1+\gamma_5}{2} \right] f Z_\mu \right. \\ &+ \left. \bar{f} \gamma^\mu \left[ a_{2L}(f) \frac{1-\gamma_5}{2} + a_{2R}(f) \frac{1+\gamma_5}{2} \right] f Z'_\mu \right\} \\ &= \frac{g}{c_W} \left\{ \bar{f} \gamma^\mu [g_{1V}(f) + g_{1A}(f)\gamma_5] f Z_\mu \right. \\ &+ \left. \bar{f} \gamma^\mu [g_{2V}(f) + g_{2A}(f)\gamma_5] f Z'_\mu \right\}. \quad (11) \end{aligned}$$

where  $g_{1V}(f) = (a_{1L} + a_{1R})/2$ ,  $g_{1A}(f) = (a_{1R} - a_{1L})/2$ ,  $g_{2V}(f) = (a_{2L} + a_{2R})/2$  and  $g_{2A}(f) = (a_{2R} - a_{2L})/2$  are defined as [8]

$$\begin{aligned} a_{1L,R}(f) &= T^3(f_{L,R}) - s_W^2 Q(f), \\ a_{2L,R}(f) &= -c_W^2 \left[ \frac{3X(f_{L,R})}{\sqrt{3-4s_W^2}} - \frac{\sqrt{3-4s_W^2}}{2c_W^2} Y(f_{L,R}) \right], \quad (12) \end{aligned}$$

where  $Y = 2X - \lambda_8/\sqrt{3}$ . The couplings are presented in Table I and Table II.

TABLE I: The couplings of  $Z$  with fermions

f	$g_{1V}(f)$	$g_{1A}(f)$
$e, \mu, \tau$	$-\frac{1}{4} + s_W^2$	$\frac{1}{4}$
$\nu_e, \nu_\mu, \nu_\tau$	$\frac{1}{4}$	$-\frac{1}{4}$
u, c, t	$\frac{1}{4} - \frac{2s_W^2}{3}$	$-\frac{1}{4}$
d, s, b	$-\frac{1}{4} + \frac{s_W^2}{3}$	$\frac{1}{4}$
T	$-\frac{2}{3}s_W^2$	0
$D_i$	$\frac{1}{3}s_W^2$	0

TABLE II: The couplings of  $Z'$  with fermions

f	$g_{2V}(f)$	$g_{2A}(f)$
$e, \mu, \tau$	$(-\frac{1}{4} + s_W^2) \frac{1}{(3-4s_W^2)^{1/2}}$	$\frac{1}{4(3-4s_W^2)^{1/2}}$
$\nu_e, \nu_\mu, \nu_\tau$	$-\frac{(3-4s_W^2)^{1/2}}{4}$	$\frac{(3-4s_W^2)^{1/2}}{4}$
t	$-\frac{3+2s_W^2}{12(3-4s_W^2)^{1/2}}$	$(\frac{1}{2} - s_W^2) \frac{1}{2(3-4s_W^2)^{1/2}}$
b	$-\frac{(3-4s_W^2)^{1/2}}{12}$	$\frac{1}{4(3-4s_W^2)^{1/2}}$
u, c	$(\frac{1}{4} - \frac{2s_W^2}{3}) \frac{1}{(3-4s_W^2)^{1/2}}$	$-\frac{1}{4(3-4s_W^2)^{1/2}}$
d, s	$(\frac{1}{4} - \frac{s_W^2}{6}) \frac{1}{(3-4s_W^2)^{1/2}}$	$-(\frac{1}{2} - s_W^2) \frac{1}{2(3-4s_W^2)^{1/2}}$
T	$(3 - 7s_W^2) \frac{1}{6(3-4s_W^2)^{1/2}}$	$-\frac{c_W^2}{2(3-4s_W^2)^{1/2}}$
$D_i$	$-\frac{3-5s_W^2}{6(3-4s_W^2)^{1/2}}$	$\frac{c_W^2}{2(3-4s_W^2)^{1/2}}$

To get interactions among Higgs bosons with the  $Z$  and the extra  $Z'$ , we consider

$$\mathcal{L}_{Higgs} = (D_\mu \eta)^\dagger (D^\mu \eta) + (D_\mu \rho)^\dagger (D^\mu \rho) + (D_\mu \chi)^\dagger (D^\mu \chi) \quad (13)$$

where the covariant derivatives of triplets are given by

$$D_\mu \phi = \left( \partial_\mu + ig \sum_{a=1}^8 W_\mu^a \frac{\lambda_a}{2} + ig_X X B_\mu \frac{\lambda_9}{2} \right) \phi \quad (14)$$

$$= \partial_\mu \phi + \text{diag}(a^1, a^2, a^3)_\mu \phi + M_\mu \phi \quad (15)$$

where  $\lambda_a$ ,  $a = 1, \dots, 8$  are Gell-Mann matrices,  $\lambda_9 = \sqrt{2/3} \text{diag}(1, 1, 1)$ ,

$$\begin{aligned} a_\mu^1 &= i\frac{g}{2} \left( W_\mu^3 + \frac{1}{\sqrt{3}} W_\mu^8 + \frac{gX}{g} \sqrt{\frac{2}{3}} X B_\mu \right), \\ a_\mu^2 &= i\frac{g}{2} \left( -W_\mu^3 + \frac{1}{\sqrt{3}} W_\mu^8 + \frac{gX}{g} \sqrt{\frac{2}{3}} X B_\mu \right), \\ a_\mu^3 &= i\frac{g}{2} \left( -\frac{2}{\sqrt{3}} W_\mu^8 + \frac{gX}{g} \sqrt{\frac{2}{3}} X B_\mu \right), \end{aligned} \quad (16)$$

$$M_\mu = i\frac{g}{\sqrt{2}} \begin{pmatrix} 0 & W_\mu^+ & X_\mu^0 \\ W_\mu^- & 0 & Y_\mu^- \\ X_\mu^{0*} & Y_\mu^+ & 0 \end{pmatrix}, \quad (17)$$

where the non-self-conjugated gauge bosons  $W^+$ ,  $Y^-$ ,  $X$  are defined as

$$\begin{aligned} \sqrt{2} W_\mu^+ &= W_\mu^1 - iW_\mu^2, \quad \sqrt{2} Y_\mu^- = W_\mu^6 - iW_\mu^7, \\ \sqrt{2} X_\mu &= W_\mu^4 - iW_\mu^5. \end{aligned} \quad (18)$$

The matching condition gives a relation between coupling constants of two groups (for the 3-3-1 model with arbitrary beta, see [9])

$$\frac{gX}{g} = \frac{3\sqrt{2}t_W}{\sqrt{3-t_W^2}}, \quad (19)$$

where  $t_W \equiv s_W/c_W$ , with  $s_W \equiv \sin\theta_W$ ,  $c_W \equiv \cos\theta_W$ .

The gauge bosons are expressed in terms of the physical ones through the relation dependent only on the electric charge form (5) but not on the Higgs structure [9]:

$$\begin{aligned} W_\mu^3 &= c_W Z_\mu + s_W A_\mu, \\ W_\mu^8 &= \sqrt{1 - \frac{t_W^2}{3}} Z'_\mu - \frac{t_W}{\sqrt{3}} (c_W A_\mu - s_W Z_\mu), \\ B_\mu &= \frac{t_W}{\sqrt{3}} Z'_\mu + \sqrt{1 - \frac{t_W^2}{3}} (c_W A_\mu - s_W Z_\mu). \end{aligned} \quad (20)$$

Hence we have

$$\begin{aligned} a_\mu^1 &= b_1 Z'_\mu + c_1 Z_\mu + d_1 A_\mu, \\ a_\mu^2 &= b_2 Z'_\mu + c_2 Z_\mu + d_2 A_\mu, \\ a_\mu^3 &= b_3 Z'_\mu + c_3 Z_\mu + d_3 A_\mu, \end{aligned} \quad (21)$$

with

$$\begin{aligned} b_1(X_\phi) &= b_2(X_\phi) = i\frac{g}{6} \frac{3 + (6X_\phi - 1)t_W^2}{\sqrt{3-t_W^2}}, \\ b_3(X_\phi) &= i\frac{g}{3} \frac{(3X_\phi + 1)t_W^2 - 3}{\sqrt{3-t_W^2}}, \\ c_1(X_\phi) &= i\frac{g}{2c_W} \left[ 1 - 2s_W^2 \left( \frac{1}{3} + X_\phi \right) \right], \\ c_2(X_\phi) &= -i\frac{g}{2c_W} \left[ 1 - 2s_W^2 \left( \frac{2}{3} - X_\phi \right) \right], \\ c_3(X_\phi) &= -ig\frac{s_W^2}{c_W} \left( X_\phi + \frac{1}{3} \right), \\ d_1(X_\phi) &= ig s_W \left( X_\phi + \frac{1}{3} \right), \\ d_2(X_\phi) &= ig s_W \left( X_\phi - \frac{2}{3} \right), \\ d_3(X_\phi) &= ig s_W \left( X_\phi + \frac{1}{3} \right), \end{aligned} \quad (22)$$

where  $X_\phi$  is the  $X$ -charge of the field  $\phi$ . To find the triple couplings of gauge bosons with Higgs we expand kinetic terms (13):

$$\begin{aligned} (D_\mu \phi)^+ (D^\mu \phi) &= [\partial_\mu \phi^+ + \phi^+ \text{diag}(a^1, a^2, a^3)_\mu^+ + \phi^+ M_\mu^+] [\partial^\mu \phi + \text{diag}(a^1, a^2, a^3)^\mu \phi + M^\mu \phi] \\ &= [\partial_\mu \phi^+ \text{diag}(a^1, a^2, a^3)^\mu \phi + H.c.] + \phi^+ \text{diag}(a^1, a^2, a^3)_\mu^+ \text{diag}(a^1, a^2, a^3)^\mu \phi \\ &\quad + [\phi^+ \text{diag}(a^1, a^2, a^3)_\mu^+ M^\mu \phi + H.c.] + \dots \end{aligned} \quad (23)$$

Expression (23) gives the triple couplings among  $Z'$  with two Higgs bosons and couplings among  $Z'$  with one Higgs and one gauge bosons. The couplings among  $Z'$  with two Higgs bosons are given by

$$a^{i\mu} \partial_\mu \phi^{i*} \phi^i + H.c. = b_i Z'^\mu \partial_\mu \phi^{i*} \phi^i + H.c. \quad (24)$$

where  $\phi^T = \langle \phi^1, \phi^2, \phi^3 \rangle$ , the sum is taken over  $i = 1, 2, 3$  and over  $\phi = \eta, \rho, \chi$ .

The couplings among  $Z'$  with one Higgs and one gauge bosons are given by

$$a_\mu^{i*} a^{i\mu} \phi_i^* \phi_i + (\phi_i^* a_\mu^{i*} M_{ij}^\mu \phi_j^j + H.c.), \quad (25)$$

where the sum is taken over  $i = 1, 2, 3$ . We see that the necessary couplings are proportional to VEVs. Keeping this in mind, from (25), we get the following couplings

1. For  $\phi \equiv \eta$ , with  $X_\eta = -\frac{1}{3}$  and we get

$$a_\mu^{1*} a^{1\mu} \eta^{0*} \eta^0 + v[(a_\mu^{1*} M_{1j}^\mu \eta^j + \eta_i^* a_\mu^{i*} M_{i1}^\mu) + H.c.](26)$$

where  $i, j = 2, 3$ .

2. For  $\phi \equiv \rho$ , with  $X_\rho = \frac{2}{3}$  and we get

$$a_\mu^{2*} a^{2\mu} \rho^{0*} \rho^0 + u[(a_\mu^{2*} M_{2j}^\mu \rho^j + \rho_i^* a_\mu^{i*} M_{i2}^\mu) + H.c.](27)$$

where  $i, j = 1, 3$ .

3. For  $\phi \equiv \chi$ , with  $X_\chi = -\frac{1}{3}$  and one gets

$$a_\mu^{3*} a^{3\mu} \chi^{0*} \chi^0 + w[(a_\mu^{3*} M_{3j}^\mu \chi^j + \chi_i^* a_\mu^{i*} M_{i3}^\mu) + H.c.], \quad (28)$$

where  $i, j = 1, 2$ .

To get couplings among  $Z'$  with Higgs bosons we have to determine the physical Higgs bosons, i.e., we have to consider the Higgs potential

$$\begin{aligned} V_{Higgs} = & \mu_1^2 \eta^+ \eta + \mu_2^2 \rho^+ \rho + \mu_3^2 \chi^+ \chi + \lambda_1 (\eta^+ \eta)^2 \\ & + \lambda_2 (\rho^+ \rho)^2 + \lambda_3 (\chi^+ \chi)^2 + (\eta^+ \eta) [\lambda_4 (\rho^+ \rho) \\ & + \lambda_5 (\chi^+ \chi)] + \lambda_6 (\rho^+ \rho) (\chi^+ \chi) + \lambda_7 (\rho^+ \eta) (\eta^+ \rho) \\ & + \lambda_8 (\chi^+ \eta) (\eta^+ \chi) + \lambda_9 (\rho^+ \chi) (\chi^+ \rho) \\ & + [f_1 \epsilon^{ijk} \eta_i \rho_j \chi_k + H.c.]. \end{aligned} \quad (29)$$

In the above potential we have neglected lepton-number violating interactions since these terms must be very small in comparison with the above terms, and this does not affect our further results much.

With VEVs given in (9), we expand the Higgs fields as follows[17]

$$\begin{aligned} \eta^0 &= v + a_\eta + ib_\eta, \\ \rho^0 &= u + a_\rho + ib_\rho, \\ \chi'^0 &= w + a_\chi + ib_\chi. \end{aligned} \quad (30)$$

Substituting (30) into the potential (29) we see the mixing between Higgs fields.[18] After diagonalization, with the approximation:  $|f_1| \sim w$ ,  $w \gg u, v$ [10], we get the following physical fields

$$\begin{aligned} \begin{pmatrix} a_\eta \\ a_\rho \end{pmatrix} &\approx \frac{1}{\sqrt{v^2 + u^2}} \begin{pmatrix} v & u \\ u & -v \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}, \\ a_\chi &\approx H_3^0, \\ \begin{pmatrix} b_\eta \\ b_\rho \end{pmatrix} &\approx -\frac{1}{\sqrt{v^2 + u^2}} \begin{pmatrix} v & u \\ u & v \end{pmatrix} \begin{pmatrix} G_1^0 \\ G_2^0 \end{pmatrix}, \\ b_\chi &\approx G_3^0. \end{aligned} \quad (31)$$

with corresponding masses:

$$\begin{aligned} m_{H_1^0}^2 &\approx 4 \frac{\lambda_2 u^4 - \lambda_1 v^4}{v^2 - u^2} \approx 4\lambda_1 (u^2 + v^2), \\ m_{H_2^0}^2 &\approx \frac{v^2 + u^2}{2vu} w^2, \\ m_{H_3^0}^2 &\approx -4\lambda_3 w^2. \end{aligned} \quad (32)$$

The sectors of single positive charged and neutral Higgs fields give the following states

$$\begin{aligned} \begin{pmatrix} \eta^+ \\ \rho^+ \end{pmatrix} &= \frac{1}{\sqrt{v^2 + u^2}} \begin{pmatrix} -v & u \\ u & v \end{pmatrix} \begin{pmatrix} G_1^+ \\ H_1^+ \end{pmatrix}, \\ \begin{pmatrix} \rho'^+ \\ \chi^+ \end{pmatrix} &= \frac{1}{\sqrt{u^2 + w^2}} \begin{pmatrix} -u & w \\ w & u \end{pmatrix} \begin{pmatrix} G_2^+ \\ H_2^+ \end{pmatrix}, \\ \begin{pmatrix} \eta'^0 \\ \chi^{0*} \end{pmatrix} &= \frac{1}{\sqrt{v^2 + w^2}} \begin{pmatrix} -v & w \\ w & v \end{pmatrix} \begin{pmatrix} G_4^0 \\ H_4^0 \end{pmatrix}, \end{aligned} \quad (33)$$

with corresponding masses

$$\begin{aligned} m_{H_1^+}^2 &= \frac{v^2 + u^2}{2vu} (f_1 w - 2\lambda_7 v u), \\ m_{H_2^+}^2 &= \frac{u^2 + w^2}{2uw} (f_1 v - 2\lambda_9 u w), \\ m_{H_4^0}^2 &= \frac{v^2 + w^2}{2vw} (f_1 u - 2\lambda_8 v w). \end{aligned} \quad (34)$$

Looking at mass spectrum (32) and (34) we see that if  $|f_1| \sim w$ , the spectrum separates into two individual blocks: one very light Higgs  $H_1^0$ . This field, namely, is the unique Higgs boson  $h$  in the SM and five other Higgs bosons having approximately the same masses and proportional to  $w$ . Thus, the suggestion  $|f_1| \sim w$  is very natural, then we only need to introduce one new mass scale  $w$  to extend group  $SU(2)_L \otimes U(1)_Y \rightarrow SU(3)_L \otimes U(1)_X$ . In the future numerical study, we will take mass of the  $H_1^0 \equiv h$  to be about 150 GeV and masses of all remain Higgs to be in the range of 600 GeV. Note that the Goldstone bosons, which are  $G_{1,2}^0$ ,  $G_3^0$ ,  $G_1^+$ ,  $G_2^+$  and  $G_4^0$ , correspond to gauge bosons  $Z$ ,  $Z'$ ,  $W^+$ ,  $Y^+$  and  $X$ , respectively. The massive states  $H_1^0$ ,  $H_2^0$ ,  $H_3^0$ ,  $H_1^+$ ,  $H_2^+$  and  $H_4^0$  are physical ones. From couplings (24) and mixing (31) and (33), in the approximation  $w \gg u \approx v$  we have coupling constants given in Table III[19].

TABLE III: The couplings of  $Z'$  with two Higgs bosons

Vertex	Coupling constant ( $g_{HH^*}$ )
$Z'_\mu (\partial^\mu H_1^+ H_1^- - \partial^\mu H_1^- H_1^+)$	$-i \frac{g}{2} \frac{t_W^2}{\sqrt{3-t_W^2}}$
$Z'_\mu (\partial^\mu H_2^- H_2^+ - \partial^\mu H_2^+ H_2^-)$	$-i g \frac{1-t_W^2}{\sqrt{3-t_W^2}}$
$Z'_\mu (\partial^\mu H_4^{0*} H_4^0 - \partial^\mu H_4^0 H_4^{0*})$	$-i g \frac{1}{\sqrt{3-t_W^2}}$

Similarly, from interactions (26) -(28) and mixing (31) and (33) we get the coupling constants of  $Z'$  to one Higgs and another gauge bosons which are given in Table IV.

From Table IV, we see that the coupling constants are always proportional to VEV and  $g^2$ . In addition, the decay channels  $Z' \rightarrow Zh$  at high energy may give contribution to production of the SM Higgs boson  $h$ . This background contribution is not small in comparison with the discovery threshold at LHC (this will be shown in our conclusions) and it is necessary to be determined in

TABLE IV: Triple coupling constants of  $Z'$ , gauge and Higgs bosons

Vertex	Coupling constant $[(g_{HG})g_{\alpha\beta}]$	Vertex	Coupling constant $[(g_{HG})g_{\alpha\beta}]$
$Z'_\mu Z^\mu H_1^0$	$ug^2 \frac{(1-t_W^2)}{\sqrt{3-t_W^2}}$	$Z'_\mu Z'^\mu H_1^0$	$ug^2 \frac{1+t_W^4}{3-t_W^2}$
$Z'_\mu Z^\mu H_2^0$	0	$Z'_\mu Z'^\mu H_2^0$	$-ug^2 \frac{2t_W^4}{3-t_W^2}$
$Z'_\mu Z^\mu H_3^0$	0	$Z'_\mu Z'^\mu H_3^0$	$wg^2 \frac{2\sqrt{2}}{3-t_W^2}$
$Z'_\mu X^\mu H_4^0$	$vg^2 \frac{\sqrt{3-t_W^2}}{\sqrt{2}}$	$Z'_\mu Y^{-\mu} H_2^+$	$ug^2 \frac{\sqrt{3-t_W^2}}{\sqrt{2}}$
$Z'_\mu X^{*\mu} H_4^{0*}$	$vg^2 \frac{\sqrt{3-t_W^2}}{\sqrt{2}}$	$Z'_\mu Y^{+\mu} H_2^-$	$ug^2 \frac{\sqrt{3-t_W^2}}{\sqrt{2}}$

the process of searching the Higgs boson in the near future. The channel  $Z'^* \rightarrow Z'h$  gives the possibility to the process  $pp \rightarrow Z'h$ . The cross section for this process, however, must be phenomenologically quite small. We will consider both processes in our numerical evaluation.

To proceed further, let us give masses of the gauge bosons after symmetry breaking [8]

$$\begin{aligned}
M_W^2 &= \frac{1}{2}g^2(u^2 + v^2), \quad M_Z^2 = \frac{g^2}{2c_W^2}(u^2 + v^2), \\
M_X^2 &= \frac{1}{2}g^2(w^2 + v^2), \quad M_Y^2 = \frac{1}{2}g^2(w^2 + u^2), \\
M_{Z'}^2 &= \frac{g^2}{2(3-4s_W^2)} \left[ 4w^2 + \frac{u^2}{c_W^2} + \frac{v^2(1-2s_W^2)^2}{c_W^2} \right] \quad (35)
\end{aligned}$$

For simplicity we suggest that

$$w \gg u \approx v \approx \frac{M_W}{g}. \quad (36)$$

Then, from (35) we get the following relation

$$M_Y \approx M_X \approx \frac{\sqrt{3-4s_W^2}}{2} M_{Z'} \approx 0.72 M_{Z'}. \quad (37)$$

Hence, by (37), the processes such as  $Z' \rightarrow XX^*, Y^- Y^+$  do not give contribution to decay width of  $Z'$ . In addition, from the rare kaon decay, the following constraint is given [11]

$$2.3 \text{ TeV} < M_{Z'} < 4.3 \text{ TeV}. \quad (38)$$

In our numerical study, we will release the lower limit to be 1 TeV. From (37) we get

$$1.6 \text{ TeV} < M_X \approx M_Y < 3.1 \text{ TeV}. \quad (39)$$

### III. DECAY WIDTH OF $Z'$

In the processes mediated by the  $Z$  and  $Z'$  neutral gauge bosons, the decay widths of these particles play very important role. Hence, we firstly discuss of decay modes of these particles. Until now, the total decay width of  $Z'$  into particles in the 3-3-1 model with RH neutrinos are not exactly and completely performed. In [7, 12], the two-body  $Z'$  decay in the 3-3-1 model with exotic leptons is considered at tree level but not complete. *The partial decay of  $Z'$  into  $H^+ Y^-$  is absent there.* Since the value  $\Gamma_{Z'}$  has very important in hadron collisions  $pp$  with intermediate field  $Z'$ , therefore we try to give the exact value for  $\Gamma_{Z'}$  at the tree level. Generally we have

$$\begin{aligned}
\Gamma_{Z'} &= \Gamma(Z' \rightarrow \nu\bar{\nu}) + \Gamma(Z' \rightarrow \bar{l}l) + \Gamma(Z' \rightarrow q\bar{q}) \\
&\quad + \Gamma(Z' \rightarrow Q\bar{Q}) + \Gamma(Z' \rightarrow G\bar{G}^*) + \Gamma(Z' \rightarrow H\bar{H}^*) \\
&\quad + \Gamma(Z' \rightarrow HG) \quad (40)
\end{aligned}$$

where  $q, Q, G, H$  stand for the usual light quarks of the SM, exotic quarks, gauge and Higgs bosons, respectively.

By the couplings (11) the decay of  $Z'$  into leptons has a general form [12]

$$\Gamma(Z' \rightarrow f\bar{f}) = m_{Z'} \frac{N_C}{12\pi} \frac{g^2}{c_W^2} \sqrt{1 - \frac{4m_f^2}{m_{Z'}^2}} \left[ |g_{2V}(f)|^2 \left( 1 + \frac{2m_f^2}{m_{Z'}^2} \right) + |g_{2A}(f)|^2 \left( 1 - \frac{4m_f^2}{m_{Z'}^2} \right) \right], \quad (41)$$

where  $N_C$  is the color number of  $f$ . In this work, masses of leptons are neglected since they are very small in comparison with the  $Z'$  mass. Masses of the exotic quarks are assumed to be equal and are in the range of 600 GeV.

Because of (37), it follows that  $\Gamma(Z' \rightarrow G\bar{G}^*) = 0$ . The

two Higgs boson decay gets a general form

$$\Gamma(Z' \rightarrow HH^*) = m_{Z'} \frac{|g_{HH^*}|^2}{48\pi} \left(1 - 4 \frac{m_H^2}{m_{Z'}^2}\right)^{3/2}. \quad (42)$$

Note that (42) is valid only for the case where two Higgs bosons have the equal masses. Finally, for the decay channels with one Higgs boson and one gauge particle, we have

$$\Gamma(Z' \rightarrow HG) = \frac{|g_{HG}|^2}{24\pi} \frac{\sqrt{E_G^2 - m_G^2}}{m_{Z'}^2} \left(2 + \frac{E_G^2}{m_G^2}\right), \quad (43)$$

where  $E_G$  is energy of the gauge boson at the final state given by  $E_G = (m_{Z'}^2 + m_G^2 - m_H^2)/2m_{Z'}$ . The total decay width of  $Z'$  in the 3-3-1 model with right-handed neutrinos is plotted in Fig. 1.

The branching ratios as function of the  $Z'$  mass are plotted in Fig. 2.

#### IV. PRODUCTION OF $Z'$ AND SM-LIKE HIGGS BOSON AT LHC

In this section we consider production of extra neutral gauge boson  $Z'$  and its contribution to the Higgsstrahlung in the 3-3-1 model with RH neutrinos at hadron colliders, namely, the single  $Z'$  production  $pp \rightarrow Z'$ ,  $pp \rightarrow Zh$  and  $pp \rightarrow Z'h$ . We first turn on the single  $Z'$  production.

##### 1. Single $Z'$ production at LHC

In contrast with the lepton colliders like  $e^+e^-$ , it is possible the single production of the  $Z$  and  $Z'$  at hadron colliders. Let us consider the available fusion subprocess

$$q + \bar{q} \rightarrow Z' \quad (44)$$

which is dominantly by  $q\bar{q}$  annihilation, and the resulting cross-section is given by

$$\hat{\sigma}(q\bar{q} \rightarrow Z') = \frac{1}{3} \frac{\pi g^2}{c_W^2} [(g_{2V}^q)^2 + (g_{2A}^q)^2] \delta(\hat{s} - M_{Z'}^2) \quad (45)$$

where

$$\hat{s} = x_1 x_2 s. \quad (46)$$

This subprocess in the minimal 3-3-1 model was considered in [14]. Because of (46) we have

$$\delta(\hat{s} - M_{Z'}^2) = \frac{1}{sx_2} \delta\left(x_1 - \frac{M_{Z'}^2}{sx_2}\right). \quad (47)$$

The total cross-section of the scattering process  $pp \rightarrow Z'X$  is given by

$$\begin{aligned} \sigma(pp \rightarrow Z') &= 2 \sum_{i=1}^5 \int_0^1 dx_1 \int_0^1 dx_2 f(i, x_1, Q) f(-i, x_2, Q) \hat{\sigma}(q_i \bar{q}_i \rightarrow Z') \\ &= \frac{2\pi g^2}{3c_W^2} \frac{1}{s} \sum_{i=1}^5 [(g_{2V}^{qi})^2 + (g_{2A}^{qi})^2] \int_{M_{Z'}^2/s}^1 f(i, x_1, M_{Z'}) f\left(-i, \frac{M_{Z'}^2}{sx_1}, M_{Z'}\right) \frac{dx_1}{x_1}. \end{aligned} \quad (48)$$

Using CTEQ6M (2004) [13] where  $t$ -quark is not included, we obtain cross-section for the above process which is plotted in Fig. 3.

##### A. Production of the SM-like Higgs boson at LHC

Next, we consider production of the SM Higgs boson at hadron colliders due to the  $Z'$  in the intermediate state,

namely

$$q(p_1) \bar{q}(p_2) \rightarrow Z, Z' \rightarrow Z(k_1) h(k_2). \quad (49)$$

The differential cross-section is given by

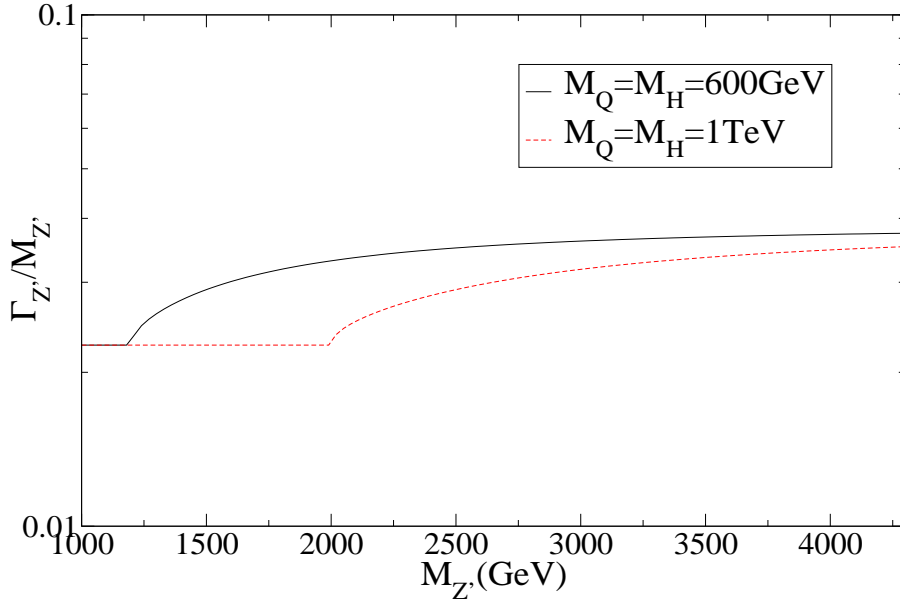


FIG. 1:  $\Gamma_{Z'}/M_{Z'}$  as a function of  $M_{Z'}$  in 3-3-1 model with RH neutrinos.

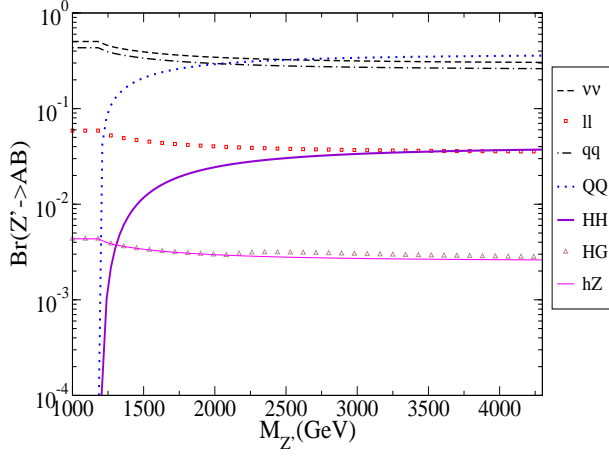


FIG. 2: Branching ratios of  $Z'$  in 3-3-1 model with RH neutrinos in the scenario  $M_Q = M_H = 600$  GeV,  $M_h = 150$  GeV.

$$\begin{aligned}
\frac{d\hat{\sigma}}{d\cos\theta} &= \frac{1}{N_C} \frac{\hat{\beta}_h g^2}{64\pi c_W^2} \frac{1}{\hat{s}} \left\{ \frac{(g_{ZZh})^2}{(\hat{s} - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \left[ \hat{s} + \frac{(M_Z^2 - \hat{t})(M_Z^2 - \hat{u})}{M_Z^2} \right] [(g_{1V}^{qi})^2 + (g_{1A}^{qi})^2] \right. \\
&+ \frac{(g_{Z'zh})^2}{(\hat{s} - M_{Z'}^2)^2 + (M_{Z'} \Gamma_{Z'})^2} \left[ \hat{s} + \frac{(M_Z^2 - \hat{t})(M_Z^2 - \hat{u})}{M_Z^2} \right] [(g_{2V}^{qi})^2 + (g_{2A}^{qi})^2] \\
&+ 2\text{Re} \left[ \frac{(g_{ZZh})(g_{Z'zh})^*}{(\hat{s} - M_Z^2 + iM_Z \Gamma_Z)(\hat{s} - M_{Z'}^2 - iM_{Z'} \Gamma_{Z'})} \right] \left[ \hat{s} + \frac{(M_Z^2 - \hat{t})(M_Z^2 - \hat{u})}{M_Z^2} \right] \\
&\left. \times [g_{2V}^{qi} g_{1V}^{qi} + g_{2A}^{qi} g_{1A}^{qi}] \right\}, \tag{50}
\end{aligned}$$

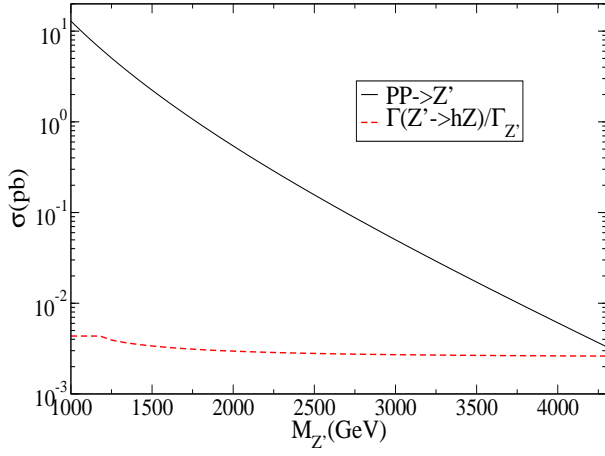


FIG. 3: Single  $Z'$  production in 3-3-1 model with RH neutrinos at LHC with  $\sqrt{s} = 14$  TeV. The dotted line indicates the  $Z'$  branching ratio into  $hZ$ .

where  $N_C = 3$  is the number of colors,  $1/N_C = 3 \times 1/3 \times 1/3$  is the averaging over colors,

$$\begin{aligned}
 \hat{s} &= x_1 x_2 s, \\
 \hat{\beta}_h &= \left(1 + \frac{M_h^2 - M_Z^2}{\hat{s}}\right) \sqrt{1 - \frac{4\hat{s}M_h^2}{(\hat{s} - M_Z^2 + M_h^2)^2}}, \\
 \hat{t} &= M_Z^2 - \frac{\hat{s} + M_Z^2 - M_h^2}{2} \left[1 - \cos\theta \sqrt{1 - \frac{4\hat{s}M_Z^2}{(\hat{s} + M_Z^2 - M_h^2)^2}}\right], \\
 \hat{u} &= M_h^2 - \frac{\hat{s} - M_Z^2 + M_h^2}{2} \left[1 + \cos\theta \sqrt{1 - \frac{4\hat{s}M_h^2}{(\hat{s} - M_Z^2 + M_h^2)^2}}\right],
 \end{aligned} \tag{51}$$

$$\begin{aligned}
 g_{ZZh} &= \frac{g}{c_W^2} M_W, \\
 g_{Z'zh} &= g M_W \frac{1 - t_W^2}{\sqrt{3 - t_W^2}}.
 \end{aligned} \tag{52}$$

After some manipulation, this formula is similar to Eq. (10) in [7]. The total cross-section for the above process has a form

$$\sigma(pp \rightarrow hZ) = 2 \sum_{i=1}^5 \int_{-1}^1 d(\cos\theta) \int_0^1 dx_1 \int_0^1 dx_2 f(i, x_1, Q) f(-i, x_2, Q) \frac{d\hat{\sigma}(q_i \bar{q}_i \rightarrow hZ)}{d\cos\theta}. \tag{53}$$

The total cross-section of the process as a function of the  $Z'$  mass is plotted in Fig. 4 The discovery limit is taken

from Ref.[15].

It is instructive to separate out the contribution of the on-shell  $Z'$ . And from these results we can estimate the

correction of  $Z'$  in the production of SM Higgs at LHC (see Fig. 5).

We also consider the production of  $hZ'$  pair as promised at LHC. Of course, this cross section should be very small. It is impossible to observe this production



at LHC (see Fig. 6).

## V. CONCLUSIONS

We have investigated the production of neutral Higgs boson at hadron colliders. Here are our results:

1. The  $Z'$  decay modes including contribution from Higgs bosons are obtained. The branching ratios for the decay modes  $Z' \rightarrow \nu\bar{\nu}$ ;  $\bar{l}l$ ;  $q\bar{q}$ ;  $Q\bar{Q}$  ( $D_1\bar{D}_1$ ,  $D_2\bar{D}_2$ ,  $T\bar{T}$ );  $HH^*$  ( $H_1^+H_1^-$ ,  $H_2^+H_2^-$ ,  $H_4^0H_4^{0*}$ ) and  $HG$  ( $H_1^0Z$ ,  $H_4^0X$ ,  $H_4^{0*}X^*$ ,  $H_2^+Y^-$ ,  $H_2^-Y^+$ ) are displayed in Fig. 2 as a function of  $M_{Z'}$  in the scenario  $M_Q = M_H = 600$  GeV,  $M_h = 150$  GeV. In the region  $M_{Z'} \in [1, 1.2$  TeV] the partial decays of  $Z'$  into  $Q\bar{Q}$  and  $HH^*$  are kinetically not allowed and  $Br(Z' \rightarrow \nu\bar{\nu}) \approx 0.5$ ,  $Br(Z' \rightarrow q\bar{q}) \approx 0.43$  are dominant.  $Br(Z' \rightarrow \bar{l}l)$  is of the order  $10^{-2}$  and the mode  $Z' \rightarrow HG$  is marginal, with a branching ratio of the order  $10^{-3}$ . When the mass of  $Z'$  is higher than 1.2 TeV the decay modes of  $Z'$  into  $Q\bar{Q}$  and  $HH^*$  start and give considerable contributions. The branching ratio  $Br(Z' \rightarrow Q\bar{Q}) \approx 0.36$ , a bit higher than  $Br(Z' \rightarrow \nu\bar{\nu})$  which slopes slightly down when  $M_{Z'}$  increases. The partial width of  $Z'$  into heavy Higgs cannot be neglected and  $Br(Z' \rightarrow HH^*) \approx Br(Z' \rightarrow \bar{l}l)$  which is nearly unchanged.

The two-body decay width of  $Z'$  is calculated and the value of  $\Gamma_{Z'}/M_{Z'}$  is shown in Fig. 1 as a function of  $M_{Z'}$  in two scenarios  $M_Q = M_H = 600$  GeV,  $M_Q = M_H = 1$  TeV and  $M_h = 150$  GeV in both cases.  $\Gamma_{Z'}$  is typically about  $2 \div 4\%$   $M_{Z'}$ . We emphasize here that if the constraint (37) is released as in [7, 12] and if we take  $M_X = M_Y = 600$  GeV then the decay modes  $Z' \rightarrow XX^*$ ,  $Y^-Y^+$  are

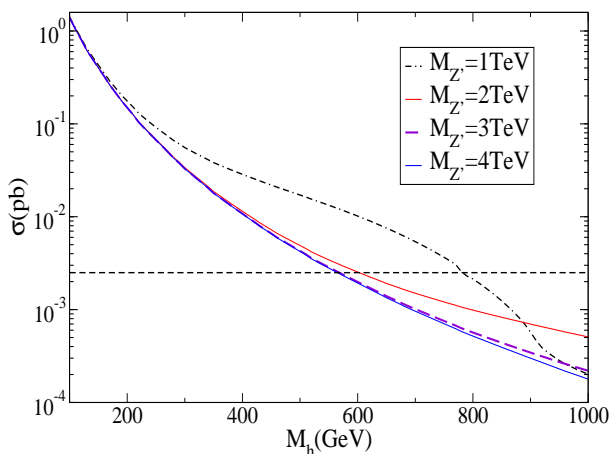


FIG. 4: Total cross section for the process  $pp \rightarrow hZ$  as a function of  $M_h$  for various values of  $M_{Z'}$  at LHC with  $\sqrt{s} = 14$  TeV in 3-3-1 model with RH neutrinos. The horizontal line indicates the cross section required for discovery: 2.5 fb.

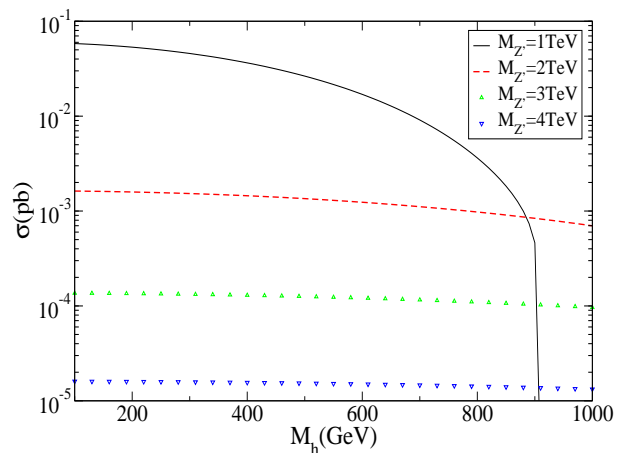


FIG. 5: The real  $Z'$  contribution to  $hZ$  production at LHC as a function of  $M_h$  for various values of  $M_{Z'}$ .

allowed. As a consequence,  $\Gamma_{Z'}$  will become very large to the values 413.74 GeV and 2.6 TeV, for the cases  $M_{Z'}$  are 2 TeV and 3 TeV, respectively.

2. Cross section for the fusion subprocess (single  $Z'$  production) is presented in Fig. 3.
3. Production the the SM-like Higgs boson is given in Fig. 4. The design luminosity at LHC is  $10$   $fb^{-1}/yr$ . We require 25 events for discovery as in [15]. This corresponds to a cross section of 2.5 fb. If the mass of  $Z'$  is not higher than 1 TeV then the process  $pp \rightarrow hZ$  is observable at LHC in the case  $M_h < 780$  GeV. If  $M_{Z'}$  is from  $2 \div 4$  TeV then the process is observable, for  $M_h < 600$  GeV. At the present constraint:  $M_h = 114_{-40}^{+56}$  [16], we see from Fig. 4 and 5 that the SM-like Higgs is mainly

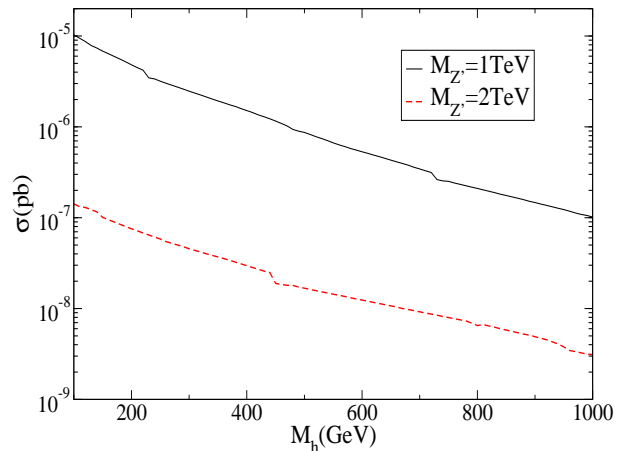


FIG. 6: Total cross section for the process  $pp \rightarrow hZ'$  as a function of  $M_h$  for various values of  $M_{Z'}$  at LHC with  $\sqrt{s} = 14$  TeV in 3-3-1 model with RH neutrinos.

produced via  $Z$  exchange. The contribution of the real  $Z'$  is about  $10^{-3} \div 10^{-1}$  pb if  $1 \text{ TeV} \leq M_{Z'} \leq 2 \text{ TeV}$  and it can be neglected in the case  $M_{Z'}$  is above that range.

4. The total cross section for the process  $pp \rightarrow hZ'$  is also displayed in Fig. 6. The cross section is about 0.01 fb, for  $M_{Z'} = 1 \text{ TeV}$ . This process is unobservable at LHC.

To finish, we hope that our results will make Higgs structure more clear when the LHC is in operation.

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 [17] In numerical calculation, one should change to normalized fields such as:  $\sqrt{2}\eta^0 = v + a_\eta + ib_\eta$   
 [18] The mixing happens between only the fields having the same electric charges  
 [19] The states of Higgs bosons are hereafter normalized.