SEARCH FOR HEAVY LEPTONS AT HADRON COLLIDERS

Paul H. Frampton\textsuperscript{(a)}, Daniel Ng\textsuperscript{(b)}, Marc Sher\textsuperscript{(c)} and Yao Yuan\textsuperscript{(c)}

\textsuperscript{(a)} Institute of Field Physics, Department of Physics and Astronomy
University of North Carolina, Chapel Hill, NC 27599-3255

\textsuperscript{(b)} TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada

\textsuperscript{(c)} Department of Physics, College of William and Mary, Williamsburg, VA 23187

Four models are considered which contain heavy leptons beyond the three families of the standard model. Two are fourth-generation extensions of the standard model in which the right-handed heavy leptons are either isosinglets or in an isodoublet; the other two are motivated by the aspon model of CP violation. In all these models, the heavy neutrino can either be heavier than, or comparable in mass to, the charged lepton leading to the possibility that the charged lepton is very long-lived. Production cross section and signatures for the heavy leptons are computed for the SSC and LHC.
I. INTRODUCTION

Since the accurate measurement of the parameters of \( Z^0 \) decay \([1]\), it has been known that there exist only three light neutrinos, \( \nu_e \), \( \nu_u \) and \( \nu_\tau \), coupling to the \( Z^0 \) in the manner prescribed by the standard model. The simplest supposition is then that the lepton sector comprises these three light neutrinos and their charged counterparts, \( e \), \( \mu \) and \( \tau \). However, it is quite possible that heavy leptons exist. Such heavy leptons, which shall be designated as \( L \) and \( N \), for the charged and neutral varieties respectively, will be a target of investigation at the next generation of particle colliders, most notably the Superconducting Super Collider (SSC) and the Large Hadron Collider (LHC). In this paper we specify four simple models which contain such heavy leptons and calculate their production cross sections at the SSC and LHC. The first two models are fourth-generation models where the right-handed \( L \) and \( N \) are doublets and singlets respectively under electroweak \( SU(2) \). The third and fourth models are inspired by the aspon model \([2]\) of CP violation.

Many analyses of heavy lepton production have previously been done \([3]\). Our work differs from Ref. \([3]\) in two respects. First, it is now known \([1]\) that the masses of any additional neutrinos must be greater than 45 GeV. It is thus quite possible that the mass of the heavy charged lepton is degenerate with or smaller than that of its neutral counterpart. In particular, the charged lepton is mass degenerate with the heavy neutrino at lowest order in models with vector-like leptons; it can be lighter in models with right-handed singlet leptons. These considerations lead to the possibility that the \( L \) could be very long-lived, perhaps not decaying inside a detector. Second, if the right-handed \( L \) and \( N \) are in an \( SU(2) \) doublet, the GIM mechanism breaks down, leading to the flavor changing decay \( L \to \tau Z \).

Discovery of such heavy leptons would revolutionize our understanding of the fundamental fermion spectrum. If they exist, it would be natural, by consideration of quark-lepton symmetry, to expect further quarks, beyond the top quark, to occur also, but in the present article we shall not consider this possibility.

The layout of the present paper is as follows: Section II discusses the four models con-
taining heavy leptons; in Section III are remarks on how detection of the heavy leptons
depends crucially on their lifetime which could lie within a wide range, depending on the
details of the mass spectrum; the production cross section formulae are presented in Section
IV; finally, the results are provided in Section V.

II. THE MODELS

In the standard model, each of the three generations of quarks and leptons mimics the
first generation in which the leptons transform under $SU(2) \times U(1)$ as one doublet ($\nu_e$, $e^-$) with $Y = -1$ ($Q = T_3 + \frac{1}{2}Y$) and a singlet $e^+$ with $Y = +2$.

It is still unclear whether the $\nu_i$ ($i = e, \mu, \tau$) are strictly massless or if there exist nonzero
neutrino masses. Evidence for the latter comes from at least two sources: the solar neutrino
measurements which suggest a solar neutrino flux below that predicted by the standard solar
model [4]; the recent gallium experiment results from SAGE [5] and GALLEX [6] lend some
support to the deficit established at the Davis chlorine experiment [7] and at the Kamiokande
water detector [8], suggesting neutrino oscillations between massive neutrinos. A popular
oscillation mechanism is that of MSW [9] where the electron neutrinos partially convert to
muon neutrinos within the interior of the Sun. Another evidence for a massive neutrino is
the 17 keV neutrino claimed in the Simpson experiment [10] and later experiments, but not
reproduced in other efforts [11]. All in all, none of these claims clearly disproves that the
first three neutrinos are massless. On the other hand, we know from $Z^0$ decay measurements
[11] that any fourth neutrino coupling normally to $Z^0$ must be heavier than $M_Z/2 \sim 45$ GeV.

In our first model (model 1), we shall suppose that the fourth-generation leptons fall into
the following representations

$$
\begin{pmatrix}
N \\
L
\end{pmatrix}_L, \quad L_R, \quad N_R,
$$

similar to the three light families except for the inclusion of the right-handed neutrino $N_R$
which allows a Dirac neutrino mass.

The second model (model 2) will instead assume representations

\[
\begin{pmatrix} N \\ L \end{pmatrix}_L, \begin{pmatrix} N \\ L \end{pmatrix}_R.
\] (2.2)

They are called vector leptons because both the left- and right- handed components transform identically under $SU(2)_L$.

Our third and fourth models are inspired by the aspon model [2] of CP violation. To solve the strong CP problem, the aspon model incorporates vector quarks at a scale of a few hundred GeV. Only colored states contribute to the relevant anomaly so that leptons are not required in solving the strong CP problem but by quark-lepton symmetry we may expect that such a model possesses also vector leptons. The vector quarks may be in $SU(2)$ doublets or singlets. So there is a corresponding choice for the heavy leptons. Our third model (model 3) will therefore contain vector lepton doublets as in Eq. (2.2) above, appended to the aspon model of Ref. 2. Finally, the fourth model (model 4) will contain singlets

\[
L_L, N_L, L_R, N_R,
\] (2.3)

added to the aspon model with $SU(2)$-singlet vector quarks.

III. DETECTION

In this section, we first note that $L$ could be very long-lived. If it is lighter than the $N$, and if both $N$ and $L$ do not mix with the standard model leptons, then $L$ would be absolutely stable. This would be a cosmological disaster; cosmological and astrophysical arguments [12] limit the lifetime to under 100 years. In the models we are considering in this paper, it is quite natural to have mixings, and thus the lifetime of $L$ is model dependent. Knowing the lifetime is crucial for experimental detection: if it is under $10^{-13}$ seconds, the $L$ will decay at the vertex; if it is between $10^{-13}$ and $10^{-8}$ seconds, it will decay in the middle
of the detector; if it is greater than $10^{-8}$ seconds, it will pass through the detector, and will look like a muon.

Let us first consider model 1. If the $N$ is heavier than the $L$, and if it does mix with a lighter neutrino (taken to be $\nu_\tau$), the $L$ lifetime will be increased by a factor of $\sin^2 \theta$ (where $\theta$ is the mixing angle) over the lifetime it would have if the $N$ were massless. For a 100 GeV $L$, this gives a lifetime of $O(10^{-21} \text{ sec.})/\sin^2 \theta$. What are plausible values of $\sin^2 \theta$? In see-saw type models, $\sin^2 \theta$ is given by either $m_{\tau}/m_L$ or by $m_{\nu_\tau}/m_N$, depending on whether the mixing can occur in the charged lepton sector or whether it is confined to the neutrino sector. In the former case, the lifetime is $O(10^{-19})$ seconds; i.e. $L$ will decay at the vertex. However, in the latter case, the lifetime is $O(10^{-11} \text{ sec.})$ ($10 \text{ eV}/m_{\nu_\tau}$). Therefore the lifetime is at least $10^{-12}$ seconds, and could easily be long enough that the $L$ would pass through any detector.

In the case in which the $L_R$ and $N_R$ form a doublet (model 2 and model 3), the masses are degenerate at tree level. The $L$ and $N$ will acquire a mass splitting from radiative corrections. This gives a splitting of $O(200) \text{ MeV}$; the precise splitting depends on masses and on the particle content of the model. This splitting gives a lifetime between $10^{-12}$ seconds and $10^{-6}$ seconds, covering the entire range of interest.

One can thus see that all three lifetimes: (a) decay at the vertex, (b) decay in the detector and (c) decay outside the detector are all plausible, and each possibility must be considered.

If $L$ decays before leaving the vertex, the analysis of the detection will be the same as that for a conventional heavy lepton, with one crucial exception. The heavy $L$’s transform differently from the standard model charged leptons in models 2, 3 and 4, and the GIM mechanism will break down, leading to flavor changing decays such as $L \rightarrow \tau Z$.

By neglecting the mass of $\tau$, one finds the ratio (for $m_L > m_Z$):

$$\frac{\Gamma(L \rightarrow \tau Z)}{\Gamma(L \rightarrow \nu_\tau W)} = \frac{|U_{L\tau}|^2}{2\cos^2 \theta_W |U_{L\nu_\tau}|^2} \frac{(m_L^2 - 2m_Z^2 + m_W^2/m_{\nu_\tau}^2)(m_L^2 - m_Z^2)}{(m_L^2 - 2m_Z^2 + m_W^2/m_{\nu_\tau}^2)(m_L^2 - m_W^2)}.$$ \hspace{1cm} (3.1)

An estimate of the value of $U_{L\tau}$ can be made by analogy with similar GIM violation in the aspon model \[3\] which gives $U_{L\tau} = (m_{\tau}/m_L)x_\tau$, where $x_\tau$ gives the ratio of $M_{34}$ to $M_{44}$ in
the lepton mass matrix. $U_{L\nu}$ is expected to be of order of $\sqrt{m_\tau/m_L}$ or $\sqrt{m_{\nu_\tau}/m_N}$. In the former case, one finds the branching ratio to be of the order of a few percent; in the latter it is nearly one hundred percent. Even if we take a small branching ratio, the background for a particle decaying into $Z\tau$ would be extremely small (especially if a vertex detector could pick up the tau). A major problem with the conventional heavy lepton detection has been backgrounds; the $L \to \tau Z$ signal, even with a branching ratio as low as 1%, may be easy to pick up.

If the decay is in the middle of the detector, but away from the vertex, it should be easy to detect. An apparent muon will suddenly decay into missing energy and a real or virtual $W$. The backgrounds should be negligible.

If the decay is outside the detector, the $L$ will be indistinguishable from a muon. The production cross section, as will be shown in the next section, is large enough that thousands of $L$'s could be produced annually at the SSC, but it is small compared with muon pair production, so the “extra” muons would not be noticed. One possible method of detection would be time-of-flight. Many of the $L$'s will have $\beta < 1$ (see Section V for $d\sigma/d\beta$), and if timing is installed in the detectors, the $L$’s could be seen. It is interesting that 1000’s of $L$’s could be produced, but that they could be missed if timing is not present.

**IV. PRODUCTION CROSS SECTIONS**

In this paper, we consider the production processes for $pp \to L^+L^-, NN, NL^\pm$, as well as $pp \to L^+L^-A, NNA$ and $NLA$ where $A$ is the aspon in models 3 and 4. The cross sections and Feynman graphs for all relevant subprocesses are given in Appendix A and Figure 1 respectively. The total cross sections for all the above processes are computed by using EHLQ[13] parton structure functions(set 1).

For model 1, gluon fusion production (see Fig. 1-a), by $Z$ and $H$ exchange, is more important because the cross sections are proportional to the square of the lepton mass. For the vector lepton models (models 2, 3 and 4), gluon fusion will not contribute, since vector
leptons do not couple to $H$ and a vectorlike coupling to the $Z$ gives no contribution due to Furry’s theorem. Thus, the only contributions for the pair production of leptons in these models are by quark fusion (see Fig. 1-b) in which the cross sections fall off faster.

In addition, an aspon $A$ can be produced through the bremsstrahlung effect from the heavy leptons (see Fig. 1-c). For completeness, we include also the production cross sections for $pp \rightarrow L^+L^-A$, $NNA$ and $NLA$ at the SSC and LHC.

As we discussed in the previous sections, a long-lived charged lepton can only be discovered if there are timing facilities in detectors. A long-lived charged lepton is more likely to appear in the vector lepton doublet models such as models 2 and 3. The velocity distribution, $d\sigma/d\beta$, where $\beta$ is defined as the ratio of the momentum to the energy of $L$ in lab-frame, has been calculated at the LHC and SSC energies for $m_L = 100, 300$ and 500 GeV; the results are reported at the end of the following section.

V. RESULTS AND CONCLUSIONS

The results for the production cross sections at the SSC ($\sqrt{s} = 40$ TeV) and the LHC ($\sqrt{s} = 17$ TeV) are displayed for the different final states of $pp$ collisions in Figs. 2-6. From these figures one can estimate easily the number of events per collider-year using the projected luminosities of the two machines (SSC: $10^{33}$ cm$^{-2}$s$^{-1}$; LHC: $10^{34}$ cm$^{-2}$s$^{-1}$) and the corresponding annual integrated luminosities 10 fb$^{-1}$ y$^{-1}$ and 100 fb$^{-1}$y$^{-1}$ respectively.

For heavy $L$ or $N$, the cross sections for $pp \rightarrow L^+L^-$, $NN$ are largest for model 1 because of the dominant gluon fusion contribution (with $Z$ and $H$ exchange) in which cross sections are proportional to the square of the masses; there is no such contribution for vector leptons (model 2, 3 and 4) because both the $Z$ and $H$ diagrams (Fig. 1-a) vanish, as discussed earlier. In particular, for $pp \rightarrow L^+L^-$ (Fig. 2) and $M_L = 400$ GeV there are predicted to be 10,000 events for model 1 per year at the SSC and the LHC. For models 2, 3 and 4 (where the gluon fusion contributions vanish), there are 1,000 or 2,000 events for model 2 and 3; and 500 or 1,000 events for model 4 at the SSC or the LHC respectively. Similar rates are

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predicted for $pp \rightarrow NN$ (which is not allowed in model 4) although the photon contribution vanishes. Finally, the cross sections for $pp \rightarrow NL^\pm$, which are allowed by $W$ exchange, can be read off from Fig. 4. Although the luminosity is ten times higher at the LHC, the number of heavy leptons produced in general is just two times that at the SSC.

Note that although the cross sections for model 2, 3 and 4 are considerably smaller, these models do have an $L \rightarrow \tau Z$ decay mode, and thus possibly a much cleaner signature, if it decays in the detector. For $pp \rightarrow NL^\pm$ in which only the $W$ exchange is allowed, models 1, 2 and 3 give similar cross sections.

For $pp \rightarrow L^+L^-A, NNA$ and $NLA$ with an aspon in the final state, the cross sections, which are shown in Figs. 5, 6 and 7 respectively, are about 100 times smaller than without an aspon, but are still within the range of detectability of SSC and LHC. model 3 (heavy lepton doublets) gives a slightly larger cross section than model 4 (heavy lepton singlets) because the former allows certain $W$ and $Z$ couplings.

If timing facilities are installed in detectors, the $\beta$ distribution functions $1/\sigma(d\sigma/d\beta)$ would be relevant. In Fig. 8, we plot the $\beta$ distributions for $pp \rightarrow L^+L^-$ in the vector doublet models (models 2 and 3) for $m_L = 100, 300$ and $500$ GeV at the LHC (Fig. 8-a) and the SSC (Fig. 8-b). For a muon, the distribution is, of course, a delta function at $\beta = 1$; whereas the $\beta$ distribution spreads out to $\beta < 1$ for a heavy lepton with an enhancement near $\beta = 1$. From Fig. 8 we conclude that in searching for a long-lived charged lepton, time-of-flight is a valuable method because of the characteristic spreading to $\beta < 1$; at SSC this is viable up to at least $m_L = 500$ GeV. Thus timing in the SSC detector would be particularly useful.

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APPENDIX A:

The cross sections for the various subprocesses are listed below.

\( gg \to L^+L^- \) and \( gg \to NN \)

This production mechanism, by Z and H exchange, is allowed in model 1 only. The cross sections by Z and H exchange are given respectively by

\[
\hat{\sigma}_Z(gg \to L^+L^-) = \frac{\beta \alpha^2 \alpha_s^2 m_L^2}{2048 \pi \sin^4 \theta_W m_W^4} |I|^2, \quad (A1)
\]

\[
\hat{\sigma}_H(gg \to L^+L^-) = \frac{\beta^3 \alpha^2 \alpha_s^2 m_L^2}{4608 \pi \sin^4 \theta_W m_W^4 ((\hat{s} - m_H^2)^2 + \Gamma_H^2 m_H^2)} |J|^2, \quad (A2)
\]

where \( \sqrt{\hat{s}} \) is the center of mass energy available for the subprocess and \( \beta \) defined as \( \beta = \sqrt{1 - 4m_L^2/\hat{s}} \) is the velocity of \( L \). \( I \) and \( J \) are given by

\[
I = 2 \sum_q (\pm) \int_0^1 dx \int_0^{1-x} dy \frac{xy}{xy - m_q^2/\hat{s}}, \quad (A3)
\]

\[
J = 3 \sum_q \int_0^1 dx \int_0^{1-x} dy \frac{1 - 4xy}{1 - xy \hat{s}/m_q^2}. \quad (A4)
\]

The sum runs over all known quarks and top-quark \( (m_t = 100 \text{ GeV is assumed}) \). The +(-) sign in the above equation applies to the quarks with isopins \( T_3 = 1/2(-1/2) \).

\( \hat{\sigma}_Z(gg \to NN) \) and \( \hat{\sigma}_H(gg \to NN) \) are the same as Eqs. (A1) and (A2) respectively with \( m_L \) replaced by \( m_N \).

\( q\bar{q} \to L^+L^- \) and \( q\bar{q} \to NN \)

The cross section for \( q\bar{q} \to L^+L^- \) (and \( q\bar{q} \to NN \), see below) is given by

\[
\hat{\sigma}(q\bar{q} \to L^+L^-) = \frac{2\pi \alpha^2 \beta B}{9\hat{s}} \left( q_i^2 - \frac{q_i \hat{s} (\hat{s} - m_L^2) (g_L^q + g_R^q) (g_L^q + g_R^q)}{2 \sin^2 \theta_W \cos^2 \theta_W ((\hat{s} - m_Z^2)^2 + \Gamma_Z^2 m_Z^2)} \right) + \frac{\pi \alpha^2 \beta (g_L^q + g_R^q)^2 (B (g_L^q + g_R^q)^2 + 2\beta^2 (g_L^q - g_R^q)^2)}{36 \sin^4 \theta_W \cos^4 \theta_W ((\hat{s} - m_Z^2)^2 + \Gamma_Z^2 m_Z^2)}, \quad (A5)
\]

where \( B = 3 - \beta^2 \) with \( \beta = \sqrt{1 - 4m_{L,N}^2/\hat{s}} \), and \( q_i e \) is the charge of the quark of type \( i \). \( g_L^q = T_3 - q_i \sin^2 \theta_W \) and \( g_R^q = -q_i \sin^2 \theta_W \) are the quark and Z boson neutral coupling coefficients. For leptons, the coefficients \( g_L^l \) and \( g_R^l \) for various models are given by
\[
g^L_L = \begin{bmatrix} T_3 - Q_l \sin^2 \theta_W, & \text{model 1, 2 and 3} \\
-Q_l \sin^2 \theta_W, & \text{model 4} \end{bmatrix}, \tag{A6}
\]

and

\[
g^L_R = \begin{bmatrix} T_3 - Q_l \sin^2 \theta_W, & \text{model 2 and 3} \\
-Q_l \sin^2 \theta_W, & \text{model 1 and 4} \end{bmatrix}, \tag{A7}
\]

where \( T_3 = 1/2(-1/2) \) and \( Q_l = 0(-1) \) for \( l = N(L) \). For the process \( qq \to NN \), \( q_t = 0 \) is used in Eq. (A5) because the photon does not contribute.

**\( \bar{q}q' \to NL^\pm \)**

The cross section of this sub-process is

\[
\hat{\sigma}(\bar{q}q' \to NL^\pm) = \frac{\pi \alpha^2 |U_{qq'}|^2 \beta \hat{s} F}{24 \sin^4 \theta_W ((\hat{s} - m_W^2)^2 + \Gamma_W^2 m_W^2)}, \tag{A8}
\]

where

\[
F = \begin{cases} 
0.5 \left[ 1 + \beta^2/3 - \left( (m_L^2 - m_N^2)/\hat{s} \right)^2 \right], & \text{model 1} \\
\left[ 1 + \beta^2/3 - \left( (m_L^2 - m_N^2)/\hat{s} \right)^2 + 3m_L m_N / \hat{s} \right], & \text{model 2 and 3} \\
0, & \text{model 4}
\end{cases} \tag{A9}
\]

with \( \beta = \left[ 1 - 2(m_L^2 + m_N^2)/\hat{s} + ((m_L^2 - m_N^2)/\hat{s})^2 \right]^{1/2} \) is again the speed of the charged lepton \( L \) in the \( \bar{q}q' \) center-of-mass.

**\( q\bar{q} \to L^+L^-A, \bar{q}q \to NNA \) and \( q\bar{q}' \to NLA \)**

The amplitude squared of these sub-processes (in model 3 and 4 only), with the momenta \( p_1 + p_2 \to p_3 + p_4 + p_5 \) respectively, are given by

\[
32(G_L^2 + G_R^2)(A_1 + A_2 + A_{12}), \tag{A10}
\]

with

\[
A_1 = \frac{1}{((p_3 + p_5)^2 - m_A^2)^2} \\
\times \left[ (2p_3 \cdot p_5 - 2m_A^2)(p_1 \cdot p_4 p_2 \cdot p_5 + p_1 \cdot p_5 p_2 \cdot p_4) \right]
\]



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\[-(2m_3^2 + m_A^2)(p_1 \cdot p_3 p_2 \cdot p_4 + p_1 \cdot p_4 p_2 \cdot p_3)
- 2m_3m_4 p_1 \cdot p_2 (m_3^2 + m_A^2 + p_3)\] ,
\(A_2 = A_1(p_3 \leftrightarrow p_4, m_3 \leftrightarrow m_4)\) ,
\(A_{12} = \frac{1}{((p_3 + p_5)^2 - m_3^2)((p_4 + p_5)^2 - m_4^2)}\)
\[\times \left[-4p_4 \cdot p_5 p_1 \cdot p_3 p_2 \cdot p_3 - 4 p_3 \cdot p_5 p_1 \cdot p_4 p_2 \cdot p_4\right]
+ 2p_3 \cdot p_4 \left(p_1 \cdot p_4 p_2 \cdot p_5 + p_1 \cdot p_5 p_2 \cdot p_4 + p_1 \cdot p_3 p_2 \cdot p_5 + p_1 \cdot p_5 p_2 \cdot p_3\right)
+ (4p_3 \cdot p_4 + 2p_4 \cdot p_5 + 2p_3 \cdot p_5)\left(p_1 \cdot p_3 p_2 \cdot p_4 + p_1 \cdot p_4 p_2 \cdot p_3\right)
+ m_3 m_4 \left(-4p_1 \cdot p_5 p_2 \cdot p_5 + p_1 \cdot p_2 (2p_3 \cdot p_5 + 2p_4 \cdot p_5 + 4p_3 \cdot p_4 + 2m_A^2)\right)
+ 2m_A^2 p_3 \cdot p_4 p_1 \cdot p_2\]  

In \(A_1, A_2\) and \(A_{12}\) the heavy lepton masses are taken to be \(m_3 = m_4 = m_L\) for \(q \bar{q} \rightarrow L^+L^-A\), \(m_3 = m_4 = m_N\) for \(q \bar{q} \rightarrow NNA\) and \(m_3 = m_N, m_4 = m_L\) for \(q \bar{q} \rightarrow NLA\).

Finally, in Eq. (A10), the values of \(G_L\) and \(G_R\) are given as follows:

\[
\begin{align*}
q \bar{q} & \rightarrow L^+L^-A & G_L & \quad G_R \\
q \bar{q} & \rightarrow NNA & g_A \left(g_L^L g_L^q P - q_i e^2 / \hat{s} \right) & \quad g_A \left(g_R^L g_R^q P - q_i e^2 / \hat{s} \right) \\
q \bar{q} & \rightarrow NLA \ (\text{model 3}) & g_A g_L^L g_L^q P & \quad g_A g_L^N g_R^q P \\
q \bar{q} & \rightarrow NLA \ (\text{model 4}) & g_A g_L^2 / 2 (\hat{s} - m_W^2) & \quad 0
\end{align*}
\]

where \(P = \left(g / \cos \theta_W \right)^2 / (\hat{s} - m_Z^2)\) and \(g_L^L\) and \(g_L^N\) in model 3 and 4 are given in Eqs. (A6) for \(l = L\) and \(N\).
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FIGURE CAPTIONS

Fig.1. Feynman diagrams for all the subprocesses. (a) $gg \to L^+L^-$, and $NN$; (b) $q\bar{q} \to L^+L^-$, $NL^\pm$ and $NN$; (c) $q\bar{q} \to L^+L^-A$, $NLA$ and $NNA$.

Fig.2. Total cross sections for heavy lepton production $pp \to L^+L^-$ as a function of the charged lepton mass $m_L$ for model 1(solid lines), model 2 and 3(dashed lines) and model 4(dotted lines). The upper and lower sets are for $\sqrt{s} = 40$ TeV and $\sqrt{s} = 17$ TeV. $m_H = 100$ GeV is assumed.

Fig.3. Total cross sections for the process $pp \to NN$ as a function of the heavy neutrino mass $m_N$ for model 1(solid lines), and model 2 and 3 (dashed lines). The upper and lower sets are for $\sqrt{s} = 40$ TeV and $\sqrt{s} = 17$ TeV. $m_H = 100$ GeV is assumed.

Fig.4. Total cross sections for the process $pp \to NL^\pm$ for model 1(solid lines), and model 2 and 3(dashed lines) for (a) $m_N/m_L = 0.5$, (b) $m_N/m_L = 1$, (c) $m_N/m_L = 2$. The upper and lower sets are for $\sqrt{s} = 40$ TeV and $\sqrt{s} = 17$ TeV. $m_H = 100$ GeV is assumed.

Fig.5. Total cross sections for the process $pp \to L^+L^-A$($A = aspon$) as a function of aspon mass $m_A$ for (a)model 3 and (b) model 4 with $m_L = 50$ GeV(solid lines) and $m_L = 150$ GeV(dashed lines). The upper and lower sets are for $\sqrt{s} = 40$ TeV and $\sqrt{s} = 17$ TeV. $m_H = 100$ GeV and the coupling of the aspon $\alpha_A = 0.1$ are assumed.

Fig.6. Total cross sections for the processes $pp \to NNA$ in model 3 for $m_L = m_N = 50$ GeV(solid lines) and $m_L = m_N = 150$ GeV(dashed lines). The upper and lower sets are for $\sqrt{s} = 40$ TeV and $\sqrt{s} = 17$ TeV. $m_H = 100$ GeV and the coupling of the aspon $\alpha_A = 0.1$ are assumed.

Fig.7. Total cross sections for the processes $pp \to NLA$ in model 3 for $m_L = m_N = 50$ GeV(solid lines) and $m_L = m_N = 150$ GeV(dashed lines). The upper and lower sets are for $\sqrt{s} = 40$ TeV and $\sqrt{s} = 17$ TeV. $m_H = 100$ GeV and the coupling of the aspon $\alpha_A = 0.1$ are assumed.

Fig.8. The velocity distributions $1/\sigma(d\sigma/d\beta)$ for the process $pp \to LL$ in model 2 and 3 at (a)$\sqrt{s} = 17$ TeV , and (b)$\sqrt{s} = 40$ TeV for $m_L = 100$ GeV(solid line), 300 GeV(dashed
line) and 500 GeV(dotted line) respectively.