Prospects of detecting massive isosinglet neutrino at LHC in the CMS detector

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Abstract

A possibility to search for a heavy isosinglet (sterile) neutrino using its decay mode $\nu_s \rightarrow l^\pm + 2 \, \text{jets}$ in the $S$-channel production $pp \rightarrow W^* + X \rightarrow l^\pm \nu_s + X$ in the CMS experiment is studied. The only assumption about the heavy neutrino is its nonzero mixing with $\nu_e$ or $\nu_\mu$. The corresponding CMS discovery potential expressed in terms of the heavy neutrino mass and the mixing parameter between the heavy and light neutrino is determined. It is shown that the heavy neutrino with a mass up to 800 GeV could be detected in CMS. We also investigate the production of the heavy neutrino $N_l$ mixed with $\nu_e$ and/or $\nu_\mu$ in the $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)$ model through the reaction $pp \rightarrow W_R + X \rightarrow l^\pm N_l + X$ with the same heavy neutrino decay channel as above. We find that for $M_{W_R} < 3 \, \text{TeV}$ it is possible to discover the heavy neutrino with a mass up to $0.75 \cdot M_{W_R}$. 
1 Introduction

In the Standard Model of electroweak interactions \cite{1}, neutrinos are the only fundamental fermions which do not have a right-handed component that transforms as an isosinglet under the $SU(2)_L$ gauge group. However, heavy $SU_C(3) \otimes SU_L(2) \otimes U(1)$ isosinglet neutrinos $\nu_s$ (sterile neutrinos or isosinglet neutrinos) are predicted in many extensions of the Standard Model \cite{2}. Such isosinglet neutrino can interact with W- and Z- bosons only as a result of its nontrivial mixing with ordinary neutrinos.

An isosinglet neutrino search was performed in several experiments \cite{6}, usually in the mass range up to a value of the order of 1 GeV or a few GeV. The search for a heavy isosinglet neutrino in the highest mass range (from 80 GeV to 200 GeV) was performed by the L3 collaboration at LEP \cite{7} using the reaction

\[ e^+ e^- \rightarrow Z^* \rightarrow \nu_s (\bar{\nu}_s \rightarrow e^+ (W^- \rightarrow jet jet)). \] (1)

The corresponding Feynman diagram is shown in Fig. 1. No signal was observed and the limit on the mixing strength with $\nu_e$ was obtained as a function of the heavy neutrino mass. For a mass $m_N = 80$ GeV (maximal sensitivity point) the 95% C.L. limit on $|U_e|^2$ is $0.2 \cdot 10^{-2}$.

In this paper we study the possibility to detect heavy isosinglet neutrino at the LHC in the CMS detector. In our study we consider the case when the heavy neutrino mixes mainly with $\nu_e$ or $\nu_\mu$. As a result of the mixing of the heavy sterile neutrino with ordinary neutrinos the former can be produced at the LHC in the reaction

\[ pp \rightarrow l^{\pm} (W^{*\pm} \rightarrow \nu_s l^{\pm}) + X \] (2)

The heavy neutrino decay mode

\[ \nu_s \rightarrow l^{\pm} W^{\mp} \rightarrow l^{\pm} + 2 \text{ jets} \] (3)

is the most interesting for the sterile neutrino detection at the LHC. This decay mode leads to the signature with 2 isolated leptons and 2 jets. The invariant mass of the $l^{\pm} + 2 \text{ jets}$ distribution $m_{inv}(l^{\pm} + 2 \text{ jets})$ has a resonance structure due to the assumed existence of the heavy neutrino decay mode $\nu_s \rightarrow l^{\pm} + 2 \text{ jets}$ that allows to separate the signal from the background. The relevant Feynman diagram is shown in Fig. 2. It corresponds to the charged current decay of a heavy neutrino. W boson in the diagram is real. There is a similar diagram with two muons in the final state. Our result for a dominant mixing with $\nu_e$ practically coincide with the corresponding results for a dominant mixing with $\nu_\mu$. Two cases are possible: Dirac heavy neutrino conserving lepton number (the diagram shown in Fig. 2 corresponds to this case) and Majorana heavy neutrino not conserving the lepton number. In the latter case the charged leptons in the diagram Fig. 2 can have the same sign. We study here both cases. Note that the sensitivity for the neutral current decay mode of the heavy neutrino is significantly worse due to small branching ratio of Z boson decay into leptons. The CMS isosinglet neutrino discovery potential depends both on the mixing parameter of the isosinglet neutrino with ordinary neutrinos and isosinglet neutrino mass. We find that it would be possible to discover the isosinglet neutrino with a mass up to 800 GeV. In out estimates we took the total luminosity $L_t = 30 fb^{-1}$ (the first 2-3 years of the LHC operation).

Figure 1: Feynman diagram corresponding to the production of the isosinglet neutrino via s - channel at LEP (the L3 search) and its subsequent decay.

The possibility of detection at LHC of a heavy right-handed neutrino $N_l$ considered in the framework of the left-right symmetric model $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)$ \cite{3} has been discussed in ref. \cite{4} (see also related papers \cite{5}). The corresponding production reactions could be

\[ pp \rightarrow W_R + X \rightarrow l^+ N_l + X \rightarrow l^+ l^+ q\bar{q} + X \] (4)
Figure 2: Feynman diagram corresponding to the production of the isosinglet neutrino via $s$-channel at LHC (the CMS search) and its subsequent decay.

$$pp \rightarrow Z_R + X \rightarrow N_l N_l + X \rightarrow l^+ l^- q \bar{q}' q'' \bar{q}''' + X$$

We studied the production and detection in CMS of such $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)$ heavy neutrino mixed with ordinary neutrinos. The production reaction is $pp \rightarrow W_R + X \rightarrow l^\pm N_l + X$, the heavy neutrino decay channel being the same as for $\nu_s$. The CMS discovery potential in this case is expressed in terms of the $M_{W_R} - M_{N_l}$ region, in which the discovery is possible.

2 The simulation of signal events.

In our simulations we used PYTHIA 6.152, modified for the simulation of signal events. The dependence of the signal cross section on the heavy neutrino mass is shown in Fig. 3

![Signal cross section](image)

Figure 3: Cross section of heavy neutrino production multiplied by the branching ratio of its subsequent decay into a charged lepton and two jets for the maximal mixing $|U_l|^2 = 1$

The CMS fast detector simulation program CMSJET 4.703 was used. The following cuts on the transverse momentum were applied: 20 GeV for electrons and muons, 40 GeV for jets. Lower cut for muons, which is...
default in CMSJET, does not improve the sensitivity. The isolation of leptons in the calorimeter was determined using the cone radius 0.3 and allowing maximal \( E_t \) of 5 GeV in the cone (the CMSJET default).

3 The selection criteria and candidate event variables.

In our analysis we proceeded through the following steps:

- Events with 2 isolated leptons of the same flavour and opposite signs were selected. Events with more than 2 leptons were rejected. The invariant mass \( M_{ll} \) of these two leptons is the first candidate event variable.
- Events with at least 2 jets were selected. From all jets a pair with invariant mass \( M_{jj} \) closest to the mass of the W boson was chosen. \( \Delta M_W = |(M_{jj} - m_W)| \) is the second variable.
- From the 4-momenta of these two jets and the 4-momentum of a lepton the invariant mass \( M_{\nu\text{cand}} \) is calculated. A peak in the distribution of this mass is to be searched for (Fig. 4).
- The \( E_t^{\text{miss}} \) of an event is the last variable of our analysis.

4 The background.

The ZW production is the obvious source of background events. They were simulated with standard PYTHIA with lepton decay modes of W and hadron decay modes of Z forbidden. The variable \( M_{ll} \) was used to suppress this kind of background. In ref. 7 events with \( M_{ll} \) close to the Z mass central value were rejected. However, the tail of the Z mass distribution is rather long. At the same time the signal events usually have big \( M_{ll} \) (Fig. 4). For this reason there was simply a lower cut on \( M_{ll} \) at values well above the Z mass central value.

The \( t\bar{t} \) production turned out to be one of the most dangerous backgrounds. The first estimates were made with PYTHIA, but the final ones, used in the sensitivity estimations, with TOPREX 10. This program correctly takes into account the spin correlations between the \( t \) and \( \bar{t} \) and uses TAUOLA code for \( \tau \) decays. TOPREX gives \( \approx 15\% \) smaller number of initial (with loose cuts) candidate events than PYTHIA. Only leptonic W decay modes were allowed (including \( \tau \nu_\tau \)). It was checked that other decay modes do not contribute. One of the most powerful cuts for the rejection of this background is the upper \( E_t^{\text{miss}} \) cut (Fig. 5).

Another dangerous background is the \( Z + \text{jet} \) production. This process has a large cross section and requires a lot of simulation with PYTHIA. In order to reduce the required CPU time only events with \( Q_t > 20 \text{ GeV} \) were simulated. It was checked with loose cuts that the above cut does not change the estimated number of background events for a given luminosity. This background is suppressed by the same cut as the ZW production and by the \( P_t \) cuts on leptons and jets. In Fig. 5 one can see the long tail of the Z invariant mass in this background process and how the \( M_{ll} \) is used for its suppression.

The other possible sources of background are the \( ZH \) and \( WH \) productions. In our calculations we took \( m_H = 150 \text{ GeV} \). However, the cross sections are small and this background is not dangerous.

In Fig. 7 the distribution of candidate event invariant masses expected in CMS with \( 30 fb^{-1} \) is shown, assuming a 300 GeV heavy neutrino mixed with \( |U_\ell|^2 = 0.1 \) with electron or muon neutrino.

The only found sources of events with same sign leptons that could be a background to the production of heavy Majorana neutrino are the \( ZH \) and \( WH \) productions. Due to small cross section of these processes the search for Majorana neutrino is almost a background-free search.

5 The sensitivity estimation.

For each value of \( M_\nu \), a probability \( \epsilon \) of signal events to pass all cuts and to have \( M_{\nu\text{cand}} \) in some range around \( M_\nu \) ("good events") was calculated. The total number of background events passing the same cuts and having \( M_{\nu\text{cand}} \) in the same range was calculated for a given luminosity. The sensitivity and the discovery potential of the CMS experiment to the search for heavy isosinglet neutrino has been estimated using the method of ref. 11. Using the efficiency \( \epsilon \) the sensitivity in terms of cross section was calculated. This cross section divided by the cross section for the maximal mixing strength \( |U_\ell|^2 = 1 \) gives a limit in terms of a mixing strength. For each value of \( M_\nu \) the cuts and the \( M_{\nu\text{cand}} \) range were optimized to obtain the best sensitivity.
Figure 4: Distributions of signal events with a heavy neutrino mass $m_{\nu_s} = 300 \text{ GeV}$ (arbitrary normalization)
The 95% C.L. sensitivity as a function of $M_{\nu}$ is shown in Fig. 8. Within 10% it is the same for both the cases of mixing with an electron and muon neutrino.

The CMS 5\sigma discovery potential estimated by the same method is shown in Fig. 9.

The CMS sensitivity to the heavy neutrino production violating lepton number (Majorana case) is shown in Fig. 10 and the CMS discovery potential in Fig. 11. Here we assumed that 50% of heavy neutrinos decay with lepton number violation that leads to same sign lepton pairs. It is almost zero background search. Some background events were found in the WH sample, but their contribution is very small due to low cross section. Events with our signature and same sign leptons can be produced in the chain decays of $t\bar{t}$, one lepton being produced at the first step, in the $t$ or $\bar{t}$ decay, and another at the second step, in a B meson decay (here $B^0$ oscillations should be taken into account). However, this background is strongly suppressed by the requirement of isolation in combination with a lepton $P_t$ cut and by the cut on the missing $E_t$. 
6 The heavy neutrino production in the $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)$ model.

Another scenario with a heavy neutrino was proposed in [4]. In this scenario the heavy neutrino $N_l$ can be produced through its coupling with the heavy $W_R$ boson, the latter being coupled with quarks and three heavy neutrinos $N_i$. One of the $N_i$ neutrinos is relatively light (a few hundred GeV) and can decay through its mixing with $\nu_e$ or $\nu_\mu$, other $N_i$ are very heavy. We assumed that the lightest $N_l$ is $N_e$. We checked that the results with $N_\mu$, being the lightest do not differ much. In this scenario we have to look for a heavy Majorana neutrino producing same sign leptons. In Fig. 12 the cross sections for different masses of $W_R$ are shown. They don’t depend on the heavy neutrino mixing parameters. We don’t study $W_R$ masses below 1500 GeV, assuming that they are excluded by indirect analyses [4].

In ref. [4] the $t\bar{t}$ production was found to be the most dangerous background. The level of this background was plotted as a function of the lepton $P_t$ cut and was not yet zero with a 20 GeV cut. However, in that work the missing $E_t$ cut was not used. In our study this cut kills the $t\bar{t}$ events survived after lepton isolation cuts and the lepton $P_t$ cut.
Figure 7: Invariant mass distribution of candidate events. The heavy neutrino with a mass of 300 $GeV$ is mixed with $|U_l|^2 = 0.1$ with electron or muon neutrino. Shaded region - only background events. The normalization corresponds to $L_t = 30 fb^{-1}$
Figure 8: CMS 90% C.L. sensitivity for opposite sign lepton pairs.

Figure 9: CMS 5σ discovery plot for opposite sign lepton pairs.
Figure 10: CMS 90% C.L. sensitivity for same sign lepton pairs
Figure 11: CMS $5\sigma$ discovery potential for same sign lepton pairs
Figure 12: The dependence of the value $\sigma(pp \to W_R \to l^\pm N_l) \cdot Br(N_l \to l^\pm + 2 \text{ jets})$ on the heavy neutrino mass

7 Conclusion.

In this paper we presented the results of our study of a possibility to detect the heavy isosinglet neutrino $\nu_s$ at LHC in the CMS detector. In the first part of our study we assumed only the nonzero mixing of this neutrino with $\nu_e$ or $\nu_\mu$ neutrinos. We found that it is possible to detect sterile neutrinos with masses up to 800 $GeV$ (for the masses near this value and above it a mixing $|U|^2$ sufficient for the detection becomes unrealistically high). In the second part we assumed the existence of additional interaction with a participation of a heavy neutrino, namely the $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U(1)$ model with a heavy $W_R$ boson \cite{4}. We assumed also that this heavy neutrino $N_l$ is mixed with ordinary neutrinos $\nu_e$ or $\nu_\mu$, that makes possible the same decay mode as for $\nu_s$. We found that for $M_{W_R} < 3 TeV$ it is possible to discover in CMS the heavy neutrino $N_l$ (l is electron or muon) with a mass up to 1500 $GeV$. 
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