Searching for Heavy Neutral Lepton in the $\nu$MSM : 2 leptons 2 quarks Channel

Tanat Piumsuwan

Department of Physics and Materials Science
Chiang Mai University, Thailand

Supervisors
Albert de Roeck, Haifa Rejeb Sfar

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1 Introduction

The Neutrino Minimal Standard Model ($\nu$MSM) is an extension of the Standard Model of particle physics, by the addition of three right-handed neutrinos with masses smaller than the electroweak scale. This model introduces the smallest possible number of new particles without adding any new physical principles (such as supersymmetry or extra dimensions) or new energy scales (like the Grand Unified Scale) [2]. A Heavy Neutral lepton (HNL) can be produced only by mixing with an active neutrino. Plus, it can be either a Majorana or a Dirac particle. In case of Majorana nature, the HNL decays can lead to a very clean signature in the CMS detector containing LNV process.

![Figure 1: Particle content of the Standard Model (left) and its minimal extension in the neutrino sector, the $\nu$MSM (right).][1]

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The search for HNL in pp collision with the CMS detector is done via the production of W boson, which has a very high cross section comparing to any other physics process. In our case, the W decays to a muon and a neutrino. The Feynman diagram of the signal process is shown in figure 2 along with Drell-Yan process as the background in this study.

In this study, we are only interested in signal events with $2l2Q$ final state. It is also important to emphasize that separation between LNC (opposite sign muons) and LNV (same sign muons) signal events is essential. HNLs are produced by mixing with active neutrinos. The decay rate of an HNL to a lepton and a scalar meson final state is governed by the equation (1).

$$\Gamma^{lP} \equiv \Gamma(N_4 \rightarrow l^- P^+) = \frac{G_F^2}{16\pi} f_P^2 |V_{q'q}|^2 |V_{4l}|^2 m_4^3$$  \hspace{1cm} (1)
The proper lifetime of the HNL is $\frac{1}{\Gamma}$ which means it is $\propto \frac{1}{m^3|V_{14}|^2}$

- This explains why HNL particle has a mean proper decay length of several mm for our coupling and mass ranges of study.

- Taking into account the boost ($\gamma\beta$) factor which is relativistic effect, our HNL particle can have a mean decay length of several centimetres, which makes this analysis unique from most of other analysis.

2 Searching Strategy

The search strategy is based on two strong points.

1. The kinematic of the HNL particle, which has an exponential decay length: the search region is binned as a function of the displacement of the 2nd muon and 1 hadronic track from the $W^*$ decays.

2. The geometry of the Tracker detector, which consists of 2 main parts: the inner and outer Tracker, that are composed from Pixel and Strip layers.

From these, the search region is divided into 3 parts: the prompt region, the intermediate region, and the very displaced region. The intermediate region is the main focus here and is defined by the 2nd muon and at least 1 hadronic track with 0 Pixel layer hits, both of them are required to be contained in the same jet. The philosophy is that the 2 tracks are always clustered into a jet.

The problem is that the chosen signals must have enough number of events after the region selection for further analysis. In this case, the chosen signals are 5 GeV in $P_t$ and unboosted decay length of 18 mm, 25 mm, 69 mm, and 349 mm HNL, since their number of events of the second muon hitting no Pixel layer are sufficient to be worked with. The HNL samples used in this study and their cross section are:

<table>
<thead>
<tr>
<th>Steps</th>
<th>Samples</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HNL 18mm</td>
<td>$(7.34 \pm 0.04) \times 10^{-2}$</td>
</tr>
<tr>
<td>2</td>
<td>HNL 25mm</td>
<td>$(5.53 \pm 0.03) \times 10^{-2}$</td>
</tr>
<tr>
<td>3</td>
<td>HNL 69mm</td>
<td>$(1.98 \pm 0.01) \times 10^{-2}$</td>
</tr>
<tr>
<td>4</td>
<td>HNL 349mm</td>
<td>$(3.895 \pm 0.005) \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Since the SM processes containing 2 muons do not have a displaced muon, most of the background events left are mostly from pileups, badly reconstructed track etc. These events shall be dealt with by applying some other cuts on the events themselves. Then,
find some region in one of the distributions that have number of signal events exceeding number of background events.

Figure 3: Schematic cross section through the CMS tracker in the \( r-z \) plane. In this view, the tracker is symmetric about the horizontal line \( r = 0 \). The center of the tracker, corresponding to the approximate position of the pp (proton-proton) collision point, is indicated by a star. Two red lines divide searching region into 3 parts, which are: 1. The prompt region, 2. The intermediate region, and 3. The very displaced region. \[3\]

3 Results

Here are the list of cuts applied on the data so far. The percentages for number of events left are obtained after scaling to the luminosity of 36 \( fb^{-1} \) from 2016 run:

<table>
<thead>
<tr>
<th>Steps</th>
<th>Cuts</th>
<th>% of No. of events left</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Preliminary cuts(^1)</td>
<td>0.560 0.581 9.96 \times 10^{-3}</td>
</tr>
<tr>
<td>2</td>
<td>2\text{nd} muon and at least 1 track in the jet are having 0 Pixel layer hits</td>
<td>0.369 0.380 2.71 \times 10^{-3}</td>
</tr>
<tr>
<td>3</td>
<td>0 Pixel hits hadronic track ( P_{T} &gt; 1 \text{ GeV} ) and ( \Delta R(\text{jet}, 2\text{nd} \text{muon}) \leq 0.3 )</td>
<td>0.353 0.365 2.01 \times 10^{-3}</td>
</tr>
<tr>
<td>4</td>
<td>Chosen 2\text{nd} \text{muon is Medium}</td>
<td>0.280 0.284 1.36 \times 10^{-3}</td>
</tr>
<tr>
<td>5</td>
<td>( 27.5 \leq m_{\mu\mu} \leq 75 )</td>
<td>0.273 0.277 1.51 \times 10^{-4}</td>
</tr>
<tr>
<td>6</td>
<td>( 15 \leq \text{Jet} P_{T} \leq 60 )</td>
<td>0.258 0.265 1.13 \times 10^{-4}</td>
</tr>
<tr>
<td>7</td>
<td>Highest track ( P_{T} ) in the jet ( \leq 27 )</td>
<td>0.254 0.261 1.03 \times 10^{-4}</td>
</tr>
<tr>
<td>8</td>
<td>( 50 \leq \text{Jet} ) ( HT ) ( \leq 200 )</td>
<td>0.237 0.243 8.53 \times 10^{-5}</td>
</tr>
<tr>
<td>9</td>
<td>( 1.8 \leq \Delta R(1\text{st} \text{muon}, 2\text{nd} \text{muon}) \leq 4.4 )</td>
<td>0.233 0.238 6.84 \times 10^{-5}</td>
</tr>
</tbody>
</table>

Some distributions used in the analysis for \( m_{\mu\mu} \) is shown in figure 4.

Figure 4: Distribution of the \( m_{\mu\mu} \) before the cuts.

\(^1\)This cut requires the 1\text{st} \text{muon to has} \( P_{T} > 25 \text{ GeV} \), \( |\eta| \leq 2.4 \), and ID = tight. This also requires the 2\text{nd} \text{muon to has} \( P_{T} > 5 \text{ GeV} \), \( |\eta| \leq 2.4 \), and ID = loose. Lastly, the jet is also required to has \( |\eta| \leq 2.0 \).
After these cuts are applied on the data, there are some differences in behavior of number of tracks of and charged particle multiplicity of jets when plot together in a 2D histogram:

![2D Histograms](image)

(a) Drell-Yan  
(b) HNL 18mm  
(c) HNL 25mm  
(d) HNL 69mm  

Figure 5: Number of tracks with 0 Pixel hits and total charged particles multiplicity within the jet containing the 2nd muon

Then, a variable $\beta = \frac{\text{number of tracks with 0 Pixel hits within the jet containing the 2nd muon}}{\text{number of total charged particle multiplicity within the jet containing the 2nd muon}}$ is defined. The distributions for the opposite sign muon case and the same sign muon case of the $\beta$ variable are shown in the figure 6.

![Histograms](image)

(a) Opposite sign muons  

Figure 6: Distributions for the $\beta$ variable
There is a region where the number of events for HNL 18mm and 25mm signals are greater than the Drell-Yan background when the two muons have same sign (LNV process). A further study on the fraction between number of tracks with 0 Pixel hits and number of tracks with 3 Pixel hits will be conducted. This variable is expected to better discriminate between background-signal in general.

4 Conclusion and future work

The searching strategy used reduces significant amount of number of events for Drell-Yan background to only $6.84 \times 10^{-5}\%$, comparing to number of events for HNL 18mm and HNL 25mm signal which are only reduced down to 0.233% and 0.238%. These percentages are obtained after scaling the number of events to the luminosity of $36 \text{ fb}^{-1}$ from 2016 run. Moreover, a region from the $\beta$ distribution is found to have number of signal events exceeds the number of Drell-Yan background events. Some other cuts will be explored in the future, such as impact parameter for the 2nd muon and the hadronic track. Further study on other backgrounds like Wjets, TTbar, and singleTop will also be conducted. Then, the data MC agreement in the control region will be checked.

References

