FYS5555-Project 3: Search for heavy Majorana neutrinos on ATLAS Open Data at $\sqrt{s} = 13\text{TeV}$

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Abstract

The aim of the project is to search for heavy right-handed Majorana neutrinos using data provided by ATLAS Open Data. The considered dataset consists of 10 fb^{-1} of data from $\sqrt{s} = 10$ TeV pp collision collected by the ATLAS detector at the CERN Large Hadron Collider. The search focuses on events containing exactly two same-sign (SS) leptons with high transverse momentum p_T and two high-p_T jet. No significant deviation from the standard model is observed in the invariant mass and transverse momentum distributions.

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1 Introduction

The search of Beyond the Standard Model signals is (together with Precision Measurements), one of the biggest focuses of today's research in High Energy Physics. It is fundamental to test the predictivity of new theories and provide constraints on the free parameters they introduce (after all, a theory can be extremely neat and elegant, but reduces to mere exercise if it fails to describe Nature with a certain accuracy). Despite its accurate predictions, the Standard Model clearly appears unsatisfying as it leaves open many issues, such as the high-energy behaviour of fundamental coupling constants, or the origin of neutrino masses just to quote some. Therefore, many theorists have come out with reasonable extensions of the SM that address and effectively address and solve such issues, introducing a quantity of new free parameters on which the validity of the theory depends.

This Project is the third and last for the course on Research-Based Particle Physics at the University of Oslo [1], and it is finalized on getting some "hands on" on the methods and techniques used in High Energy Physics research. It considers the neutrino sector of the SM and the extension of the theory attempting to restore Left- and Right- handed chiral symmetry to explain the origin of neutrino masses, introducing a Majorana-like mass term based on the hypothesis that neutrinos are their own antiparticles. The theory for five different signals, together with the SM background, is simulated using Monte Carlo generators for proton-proton collisions and is then compared with a dataset with two-leptons final states from the ATLAS Open Data at $\sqrt{s} = 13\text{TeV}$ with integrated luminosity of 10fb^{-1}. Event selection on the Data and on the MC simulations is then performed, to try to isolate the signal from the SM background processes. A tentative statistical analysis is successively applied on the processed dataset. The main reference for the analysis is [3]. The code for the analysis is available in the Github folder [2].

2 Motivation and theory

2.1 Neutrino masses

The Standard Model (SM) of Particle Physics is based on the symmetry of the gauge group

$$Su(3)_C \times Su(2)_L \times U(1)_Y$$

and the spontaneous breaking of electroweak symmetry (SSB) $Su(2)_L \times U(1)_Y$ according to the Higgs mechanism explains the appearence of mass terms in the SM lagrangian like

$$\mathcal{L} \supset -m\big(\overline{\psi_R}\psi_L + \overline{\psi_L}\psi_R\big).$$

However, neutrinos are assumed to be massless and chiral right-handed neutrino ν_R are treated as singlets.

Nonetheless, the theory has proven to be extraordinarily successful until evidence for neutrino masses has emerged in 2015: the difference between weak $(\nu_e, \nu_\mu, \nu_\tau)$ and mass eigenstates (ν_1, ν_2, ν_3) (linked by the CKM matrix) predicts flavour oscillation scaling like

$$\sin \frac{(m_i^2 - m_j^2)}{4E}$$

where the indices refer to neutrino flavours. Evidence for those oscillations implies the existence of at least two non-zero mass terms.

However, the fact that that the oscillations scale with the squared mass doesn't allow us to establish a hierarchy between the three masses. Furthermore, cosmological measurements add a further constrain, forcing those values to be very small ($\lesssim$ 1eV)

2.2 Seesaw process and Majorana neutrinos

Those results imply that we should take into consideration neutrino masses as well, and we can include them in the SM lagrangian like the other fermions: after SSB we will have a Dirac mass term like

$$\mathcal{L}_D = -m_D\left(\overline{\nu_R}\nu_L + \overline{\nu_L}\nu_R\right)$$

that automatically imply the existence of a right-handed (RH) neutrino. The fact that neutrino masses are smaller than the ones of the other fermions however suggests that there might be another mechanism to generate masses. We can use the fact that right-handed neutrinos transform like singlets under gauge transformations and add "by hand" a new gauge invariant Majorana term

$$\mathcal{L}_M = -M\left(\overline{\nu_R^c}\nu_R + \overline{\nu_R^c}\nu_R\right)$$

where left-handed anti-neutrinos appear as the CP conjugate of the RH neutrino ν_R^c. Note that such a term would violate charge conservation, but being neutrinos neutral, this is not a problem.

This imply that our "new" SM lagrangian after SSB will have a term like

$$\mathcal{L}_{DM} = -\frac{1}{2}\begin{bmatrix}\nu_L & \nu_R^c\end{bmatrix}\begin{bmatrix}0 & m_D \\ m_D & M\end{bmatrix}\begin{bmatrix}\nu_L^c \\ \nu_R\end{bmatrix} + h.c.$$

The physical neutrino states will therefore be the eigenvalues of the mass matrix

$$\mathbf{M} = \begin{bmatrix}0 & m_D \\ m_D & M\end{bmatrix}$$

predicting, if we assume $M >> m_D$, a light neutrino state ν and a heavy state N where

$$m_\nu \simeq \frac{m_D^2}{M}, \qquad m_N \simeq M.$$

One way this process is implemented is by extending the SM to a Left-Right symmetry Standard Model (LRSM), where the parity symmetry is restored by adding a new gauge group $Su(2)_R$. This way a new set of gauge bosons $W_R^\pm$ (coupling only to RH particles, compensating for the full parity violation of the $W^\pm$ bosons) and Z' [5]. The Majorana mass is then predicted to be of the order of the mass of the new charged gauge bosons

$$M \sim M_{W_R}.$$

Note that since parity is violated in weak interactions at the current energy scales, the new gauge bosons must be heavier than their respective left-handed counterpart.

3 Search on ATLAS Open Data

3.1 Signal and Data

In our analysis we consider the process shown in figure 3.1, where a heavy W_R boson formed by quark fusion in a proton-proton collision decays into a lepton and a heavy Majorana neutrino N, which further decays in a lepton and a quark pair (giving rise to jets).

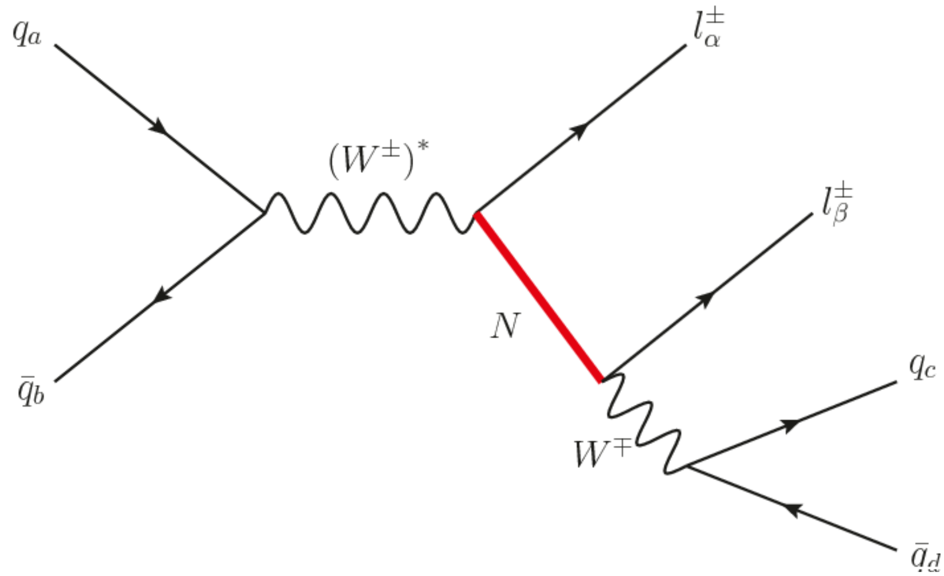


Figure 3.1: Feynman diagram of the process considered for the analysis

The dataset analyzed contains 2-lepton final states from ATLAS Open Data at $\sqrt{s} = 13\text{TeV}$ with integrated luminosity of 10fb^{-1}. The background contributions are obtained through Monte Carlo (MC) simulations including $t\bar{t}$ fusion, top decays and electroweak processes using PowHeg and Pythia generators.
The signal process is simulated using MadGraph and Pythia generators considering the LRSM for various combinations of W_R and N masses (see table 3.1).

file ID	$m_W[GeV]$	$m_R[GeV]$
309070	5000	2500
302708	4200	2100
302701	3600	1800
302687	3000	1500
302681	2400	1800

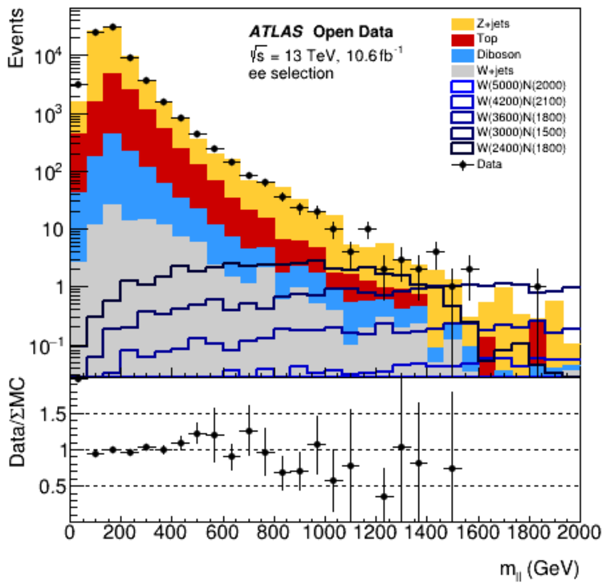
Table 3.1: Mass values used for the signal simulations

The analysis considers separately same-sign (SS) and opposite-sign (OS) leptons in the final states: if neutrinos are actually Majorana particles, there is equal probability that they decay into a lepton or an antilepton. Furthermore, since no flavour oscillations are assumed, we require the leptons on the final states to have the same flavour.

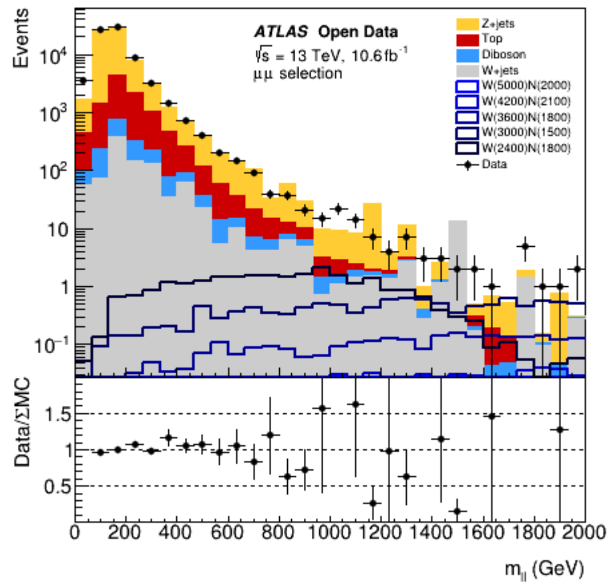
3.2 Removing background

A first cut on the events considers the geometry of the ATLAS detector [**?**], limiting the pseudorapidity η according to the sensitivity of the detecting area itself ($|\eta| < 2.5$ for the muon spectrometer, $|\eta| < 2.47$ for electron, considering the transition zone before the argon calorimeter: $1.37 < |\eta| < 1.52$). Moreover, we require high transverse momenta on the final-state leptons ($p_T > 50\text{GeV}$).

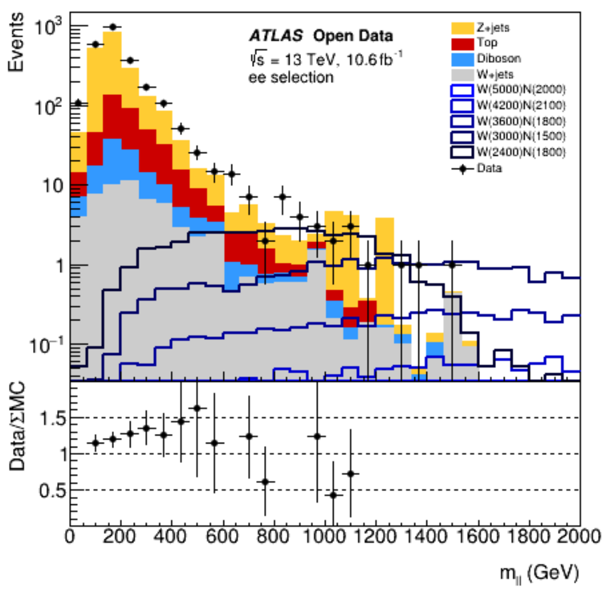
Figure 3.2 shows the invariant mass distribution of the two leptons $m(ll)$ for OS (a-b) and SS (c-d) leptons in the ee and $\mu\mu$ channel.



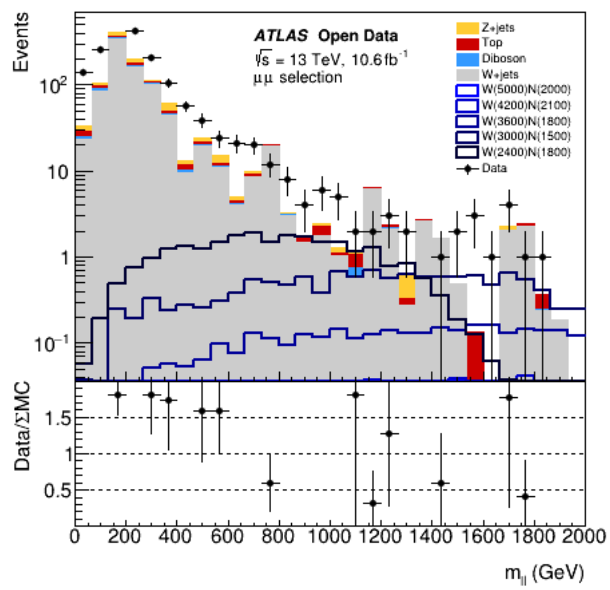
(a) OS



(b) OS



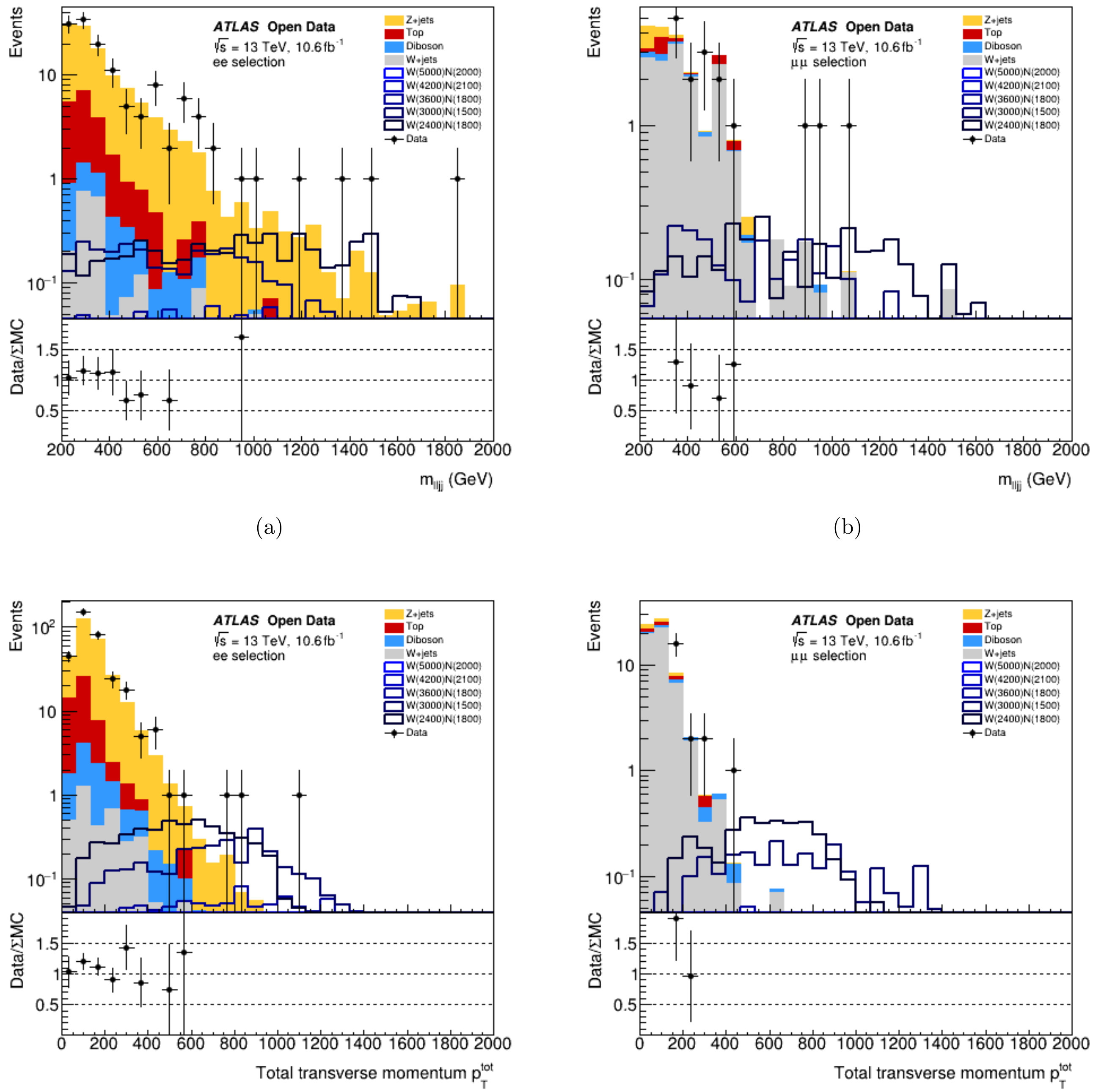
(c) SS



(d) SS

Figure 3.2: dilepton invariant mass for OS and SS final states

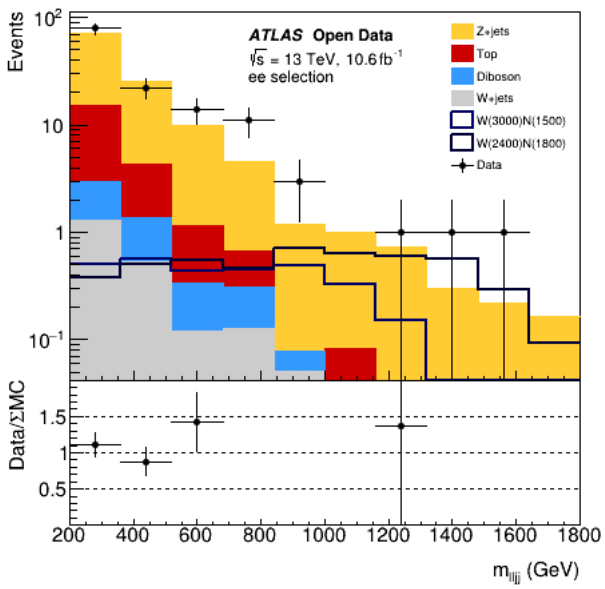
The requirement on same-sign lepton final states reduces the background by two orders of magnitude for lower invariant masses, since those final states require higher-order electroweak processes, therefore we are gonna focus our search on SS final states.
Another requirement we can add, with reference to the process in figure 3.1, is only considering processes with two high-momentum jets ($p_T > 30\text{GeV}$). Thus we will consider the distribution of the total invariant mass of the final states $m(lljj)$ and the total transverse momentum p_T^{tot}. A further cut we can do is on the double W peak, by requiring $m(lljj) > 200\text{GeV}$. Figure 3.3 shows those distributions for SS lepton final states.



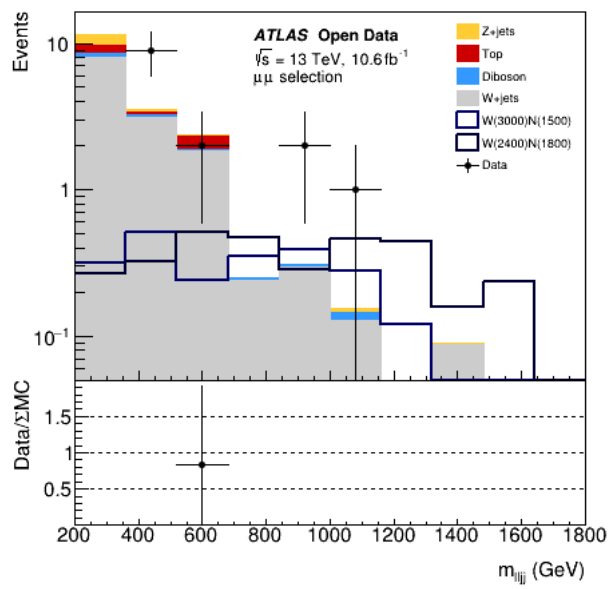
(a) (b) (c) (d)

Figure 3.3: Invariant mass (a-b) and transverse momentum (c-d) distribution for $\mu\mu$ and ee SS final states

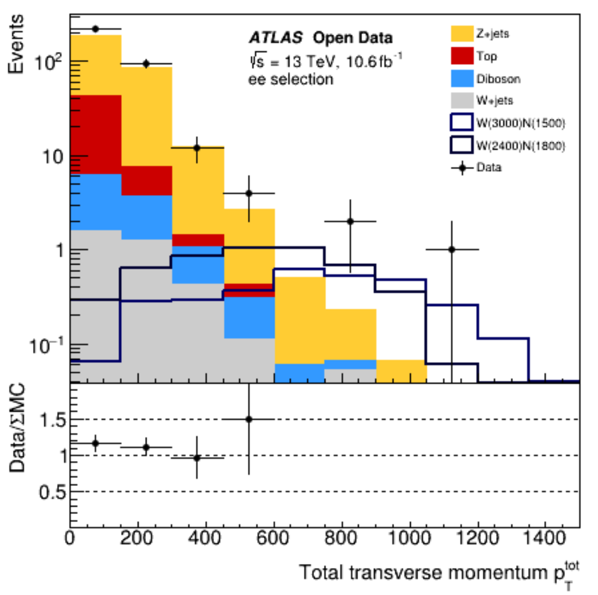
With this last requirement we have potentially managed to isolate the background signals in the energy region around 1TeV and upper, where contributions might appear from the lightest mass combinations N and W_R in our simulations. However, there are not enough data events in our selection to properly define the shape of the distribution (MC events are normalized to the data luminosity, therefore allowing us resolution beyond integer numbers). In this region our data events are either 0 or 1, which could just mean random statistical fluctuations from the SM-only signal. A tentative solution for this could be reducing the number of bins in the histograms, thus losing in energy resolution but improving the statistical interpretability of our analysis. Figure 3.4 shows the result of this operation.



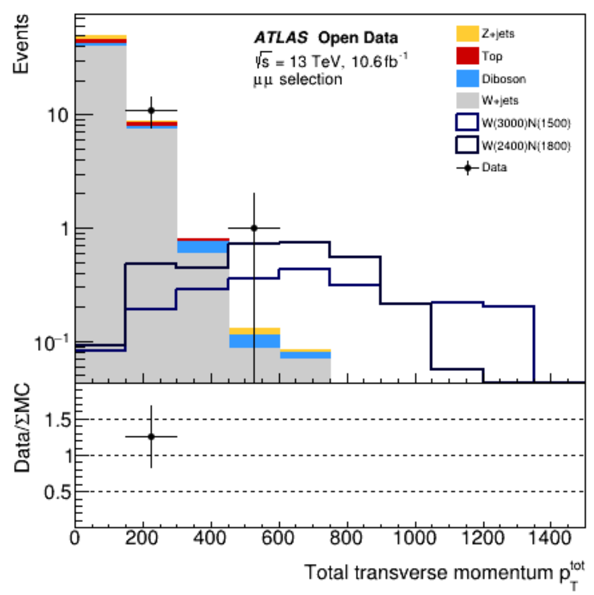
(a)



(b)



(c)



(d)

Figure 3.4: Invariant mass (a-b) and transverse momentum (c-d) distribution for $\mu\mu$ and ee SS final states after rebinning

We have now increased the number of counts to be able to perform a slightly more quantitative analysis on the compatibility between SM background and Majorana neutrinos signal. Since the muon final states present only very few data points (3 and 4), we consider the dataset with the SS electron final state.

3.3 Signal-background analysis

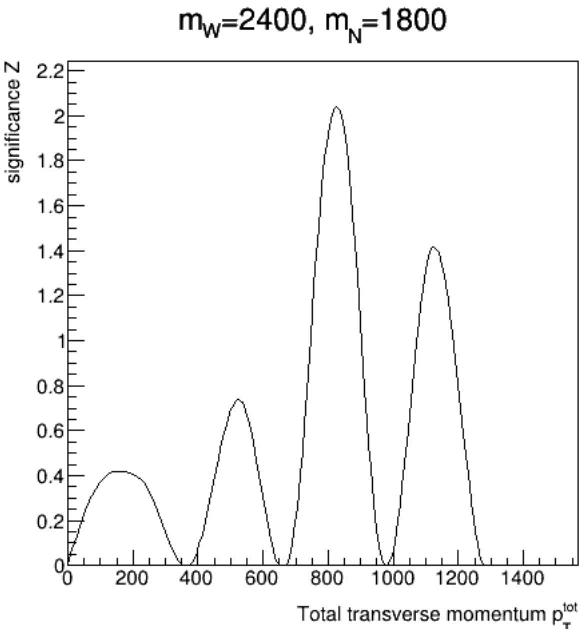
To test (and possibly reject) the background-only hypothesis, we model each bin count n as a Poisson random variable and calculate its likelihood $\mathcal{L}$ as

$$\mathcal{L}(0|\hat{\theta}) = f(n|b), \qquad \mathcal{L}(\mu|\tilde{\theta}) = f(n|s+b),$$

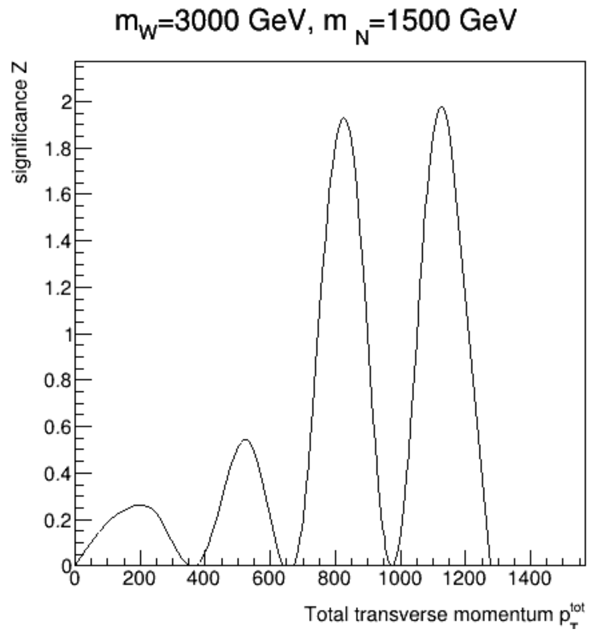
where f is the Poisson distribution and s and $s+b$ the bin counts on the MC histogram according to respectively background only and signal+background profiles. We then consider their ratio as a profile likelihood Q and calculate the significance Z:

$$q_0 = -2\log Q, \qquad Z = \sqrt{q_0}.$$

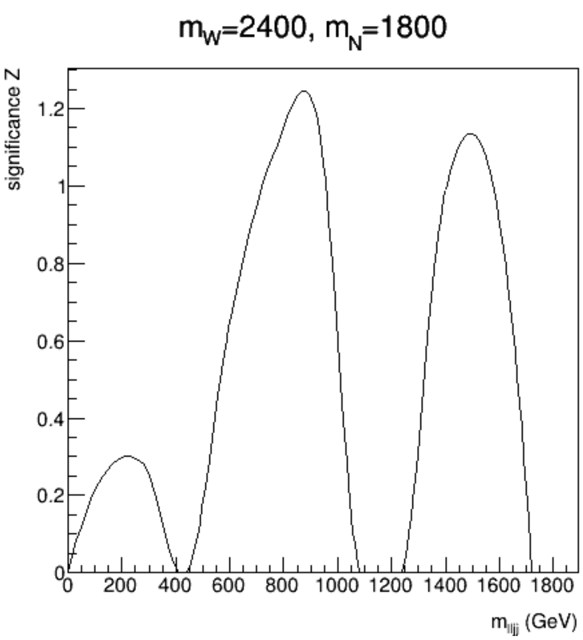
The higher the significance, the more signal-like our data will be.
Figure 3.5 shows the results of this algorithm applied to the lightest Majorana signals ($m_W = 3\text{TeV}, m_N = 1.5\text{TeV}$ and $m_W = 2.4\text{TeV}, m_N = 1.8\text{TeV}$)



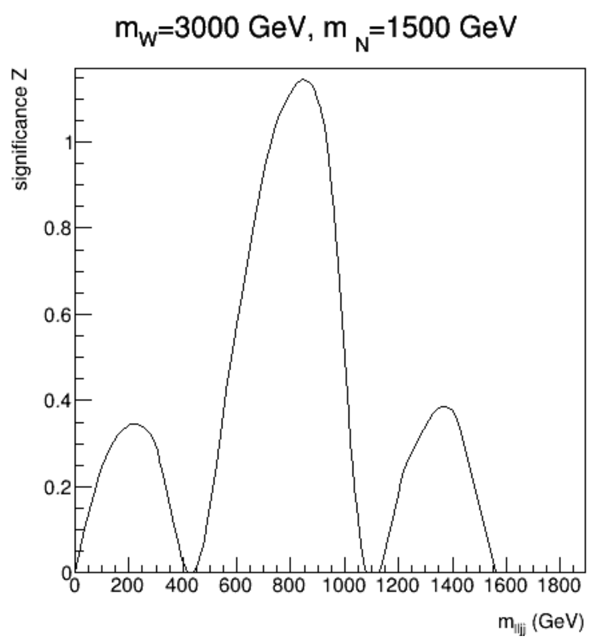
(a)



(b)



(c)



(d)

Figure 3.5: Significance scores for signal-to-background analysis for the different signals in the transverse momentum (a-b) and invariant mass (c-d) distributions.

The higher Z scores are of the order of 2, corresponding to maximum 1σ deviations from the null hypothesis (background only).

4 Conclusions

Our 1σ deviation does not allow to conclude that there is any evidence of Majorana neutrinos associated to heavy gauge bosons for the analyzed signals. A further step on the analysis could consist in retrieving information on the trigger efficiencies and systematic errors in order to define exclusion limits for the values of W_R and N masses. This would allow us to exclude a range of values for both heavy neutrino and heavy boson masses (or at least get a constraint on their mass ratio) and run the whole machinery for other signal parameters to get further constraints.
However, since one of the biggest limits of this analysis was the lacking of statistics, an even higher integrated luminosity may provide some further insights on the shape of the distributions for the same event selection. The uncertainty on the event counts for data points n scales as $\sqrt{N}$, thus we would need at least 100 more events in our final bins to reach a 10% error, that can give us enough material to base our analysis. Another possibility we may consider is to make different event selections in order to cut away a smaller amount of data from the original dataset, while still being able to isolate a potential signal, or examine in more detail the difference between SS ans OS signals.

References

[1] FYS5555-Research Based Particle Physics, University of Oslo, Spring 2019 `https://www.uio.no/studier/emner/matnat/fys/FYS5555/v19/index.html`

[2] `https://github.com/FedericoNardi/FYS5555/tree/master/Project3`

[3] ATLAS collaboration, *Search for type-III seesaw heavy leptons in pp collisions at* $\sqrt{s} = 8$TeV *with the ATLAS detector*, Phys. Rev. D, 92, 032001 (2015)

[4] M. Thomson, *Modern Particle Physics*, Cambridge University Press (2018)

[5] Pérez P, *Type III Seesaw and Left-Right symmetry*, `https://arxiv.org/pdf/0809.1202.pdf`