Searches for Fourth Generation Particles and Heavy Neutrinos at CMS Experiment

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Abstract. We present the experimental issues and discovery potentials for a fourth generation charge \(-1/3\) quark decaying to a \(W\) and a top quark and for a right-handed \(W\) that decays to a lepton and a heavy neutrino, predicted by Left-Right-symmetric models. Both produce almost background-free final states containing multiple leptons and jets. The residual backgrounds and reach for each type of particle is presented for 100 pb\(^{-1}\) of 14 TeV data.

1. Introduction
In the Standard Model (SM), at least three generations of quarks are required to produce the irreducible complex phase in the quark mixing matrix and explained the existence of \(CP\) violation. However, the known \(CP\) violation that arises from this Kobayashi-Maskawa phase is far too small by 10 orders of magnitude, by comparing to the WMAP measurements. An extra family of quarks with enlarged quark masses may resolve this big gap in a natural way \([1]\).

The searches for a fourth generation became less popular ever since the limit on the light neutrino flavors has been precisely given by direct measurements of invisible \(Z\) width \([2]\). However, such measurement does not really exclude existence of fourth generation of quarks, or a heavy neutrino with a mass greater than half of \(Z\) boson mass.

Several searches on the fourth generation quarks has been carried out by the Tevatron experiments. A direct search by CDF assuming a top-like quark decaying into a light quark and a \(W\) boson provides an exclusion limit of \(M(t' \rightarrow qW) > 311\) GeV/\(c^2\) at 95\% confidence level \([3]\). A search on the bottom-like fourth generation quark through the FCNC decay, \(b' \rightarrow bZ\), gives a limit of \(M(b') > 268\) GeV/\(c^2\) \([4]\). This result is obtained assuming a 100\% \(b' \rightarrow bZ\) decaying branching fraction and this mass limit is not really firmly established. The D0 experiment has also examined the possibility of a long-lived \(b'\) decay, and a two-dimension limits on \(M(b')\) and \(c\tau\) have been also given.

The possibility of heavy majorana neutrinos has been discussed and predicted by many theoretical models. In particular, the left-right symmetry model \([6]\) incorporates the right-handed gauge bosons, such as \(W_R\) and \(Z'\), and the heavy right-handed Majorana neutrinos, \(N_{\ell}\) (\(\ell = e, \mu, \tau\)). The discovery of neutrino oscillation indicates that the neutrinos do have non trivial masses and this is not yet in the SM. The heavy right-handed neutrinos can be the partners of the light neutrinos and the masses of light neutrinos can be generated via the See-Saw mechanism. This left-right symmetry model model, as well as many other SM extensions, the heavy Majorana neutrinos have a mass between 100 GeV/\(c^2\) and 1 TeV/\(c^2\). The LHC is a perfect place for searching these new particles.

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The best experimental limits from the D0 experiment on the right-handed $W$ boson are $M(W_R) > 739$ GeV/$c^2$ for a lepton and quark final state, and $M(W_R) > 768$ GeV/$c^2$ for pure quark final states [7].

Here we present a study on the production heavy bottom-like fourth generation quark pairs, $b\bar{b}'$, and a search for right-handed gauge boson, $W_R$, and the corresponding heavy neutrinos, $N_\ell$, with the CMS detector. The mass of the $b'$ quark is assumed to be above the top plus $W$ threshold. The decay of $b\bar{b}' \rightarrow tW^−tW^+$ is expected to be dominant, hence a four $W$ boson plus two $b$-jets final state is produced in the $pp \rightarrow b\bar{b}'$ process. Each $W$ boson can decay either leptonically ($W \rightarrow ℓν$) or hadronically ($W \rightarrow$ di-jet). Final states that contain same-sign dileptons or trileptons are rare in Standard Model processes, and hence the backgrounds are expected to be small. Hence this analysis is based on the same sign dilepton and trilepton (plus jets) signatures. A data set corresponding to 100 pb$^{-1}$ integrated luminosity is assumed for the search and exclusion limits. Three typical benchmark points are discussed in this analysis, with masses for the $b'$'s corresponding to 300, 400, and 500 GeV/$c^2$, which leads to production cross sections at $\sqrt{s} = 14$ TeV of 34.9 pb, 8.05 pb, and 2.45 pb, respectively. These cross sections are calculated with the Pythia [5] generator, at the leading-order (LO) in $α_s$.

The search for the right-handed heavy neutrinos is carried out assuming the production chain, $pp \rightarrow W_R + X \rightarrow N_\ell + ℓ + X$, and $N_\ell \rightarrow ℓ + W_R^* \rightarrow ℓ + jj$, where the $W_R^*$ is the off-shell $W_R$ boson. Such decay chain produces a signature of a high $p_T$ lepton pair with the same flavor and two high $p_T$ jets. The key parameters in the study are the masses of $W_R$ and $N_\ell$. Since the possibility of $M(W_R) < 1$ TeV/$c^2$ has been excluded by experimental searches, we only consider the region of $M(W_R) > 1$ TeV/$c^2$.

The combination of $M(N_\ell) = 500$ GeV/$c^2$ and $M(W_R) = 2000$ GeV/$c^2$ is sufficiently far from the existing limits and still well covered by the LHC energy. This “point” is studied in details and defined as a reference point (LRRP). The other two combinations with smaller masses, $M(N_\ell) = 600$ GeV/$c^2$ and $M(W_R) = 1500$ GeV/$c^2$ (LRRP1), $M(N_\ell) = 500$ GeV/$c^2$ and $M(W_R) = 1200$ GeV/$c^2$ (LRRP2), are also considered. The case of $M(N_\ell) > M(W_R)$ is not considered in this study. The signal events are generated using the Pythia generator and no k-factor is applied in the study. The signal cross section defined as the product of the total $W_R$ production cross section and the branching ratio of $W_R$ decay into lepton $ℓ$ and $N_\ell$ takes the following values for the points LRRP, LRRP1, LRRP2: 0.165 pb, 0.49 pb, 1.25 pb. The branching ratios of $W_R$ at LRRP are 0.0896 for $ℓN_\ell$ final state, and 0.9004 for quark final states. The detection of $W_R$ and $N_\ell$ signals are studied using the full CMS detector simulation and reconstruction chain. A 100 pb$^{-1}$ data set is also assumed in the estimation. More detailed descriptions of these two analysis can be found at Ref. [8, 9].

2. Search for a bottom-like fourth generation quark

For the fourth generation quark search, we require the events to pass either signal non-isolated electron trigger or single non-isolated muon trigger paths. The electron path requires at least a non-isolated electron candidate and a minimum $E_T$ of 17 GeV, while the muon path requires a non-isolated muon candidate with a $p_T$ threshold of 16 GeV/$c$. The details of CMS trigger can be found in Ref. [10].

Electrons, muons, jets, and the transverse missing energy (MET), are the major physics objects used in the fourth generation quark analysis. The transverse momentum of the electron candidates is required to be larger than 20 GeV/$c$, and the electron must be within the ECAL fiducial region ($|κ| < 2.5$). Electron candidates are cleaned further using a cut-based electron identification selection criteria. The electron candidates are required to be isolated, i.e separated from other charged tracks. Transverse momentum of the muon candidates is also required to be larger than 20 GeV/$c$, and to be in the central detector region ($|κ| < 2.0$). We require a low activity of charged tracks nearby the muon, by allowing a maximum sum $p_T$ of 3 GeV/$c$ of all
the charged tracks within a distance of $\Delta R < 0.3$ away from the muon, excluding the muon from the sum itself.

Jets are reconstructed using the iterative cone algorithm with a cone radius of 0.5 in $\Delta R$. We require a minimum $p_T$ of 35 GeV/c after jet energy scale corrections, and the jet candidates to be in the region of $|\eta| < 2.4$. The value of MET is determined from the calorimetric measurements and is corrected using the jet energy scales. A correction for the missing energy contributed by the muon candidates is further applied. A minimum MET of 40 GeV is required in the analysis.

For the same-sign dileptonic channel, exactly two leptons with the same electric charges are required. For the trileptonic channel, three leptons with the charge combinations of e.g. $\ell^+\ell^+\ell^-$ or $\ell^+\ell^-\ell^-$ are required. The events are further required to have at least four or more jets in the final state for the same-sign dileptonic channel; for the trileptonic channel, at least two or more jets are required. We require a lepton-jet separation ($\Delta R(\text{lepton,jet}) > 0.3$) in order to suppress the additional leptons from jets. Also, a lepton-lepton isolation ($\Delta R(\text{lepton,lepton}) > 0.3$) is required to reject background from doubly reconstructed muon and electron. For the trileptonic channel, an event is reject if the invariant mass of two opposite charged leptons is in within the $Z$-boson mass region. Jet multiplicities, the MET distribution, and the invariant mass of dileptons are shown in Figure 1, assuming a $b'$ mass of 300 GeV/$c^2$. The vertical dashed lines in these plots represent the final selection criteria in the analysis.

Signal events can be characterised with the observable, $H_T$, which is defined as following:

$$H_T = \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + \text{MET}. \quad (1)$$

The variable $H_T$ is the most effective one that carries the information of $b'$ mass, since the $b'$ candidates cannot be completely reconstructed in this analysis. The expected distributions for $H_T$ for 100 pb$^{-1}$ of data are shown in Fig 2. The signal is very clear for the lower mass $b'$ ($300 \sim 400$ GeV/$c^2$). The expected signal and background yields with the final selection criteria are summarized in Table 1.

### Table 1. Summary of expected signal and background yields for the search of $b'$ quark, normalized to 100 pb$^{-1}$ integrated luminosity.

| Process | Yield | Same-sign 2L | 3L | Sum |
|---------|-------|--------------|----|-----|
| $b'b', M(b') = 300$ GeV/$c^2$ | 44.7 | 23.6 | 68.2 |
| $b'b', M(b') = 400$ GeV/$c^2$ | 14.6 | 7.6 | 22.2 |
| $b'b', M(b') = 500$ GeV/$c^2$ | 5.1 | 2.9 | 8.0 |
| $t\bar{t}$+jets | | 4.7 | 1.0 | 5.7 |
| $t\bar{t}W(+j)$ | | 0.43 | 0.32 | 0.73 |
| $t\bar{t}Z(+j)$ | | 0.31 | 0.38 | 0.68 |
| $t\bar{t}W^+W^-$ | | 0.020 | 0.014 | 0.035 |
| $Z$+jets | | < 0.4 | < 0.4 | < 0.4 |
| $W$+jets | | < 1.4 | < 1.4 | < 1.4 |
| $ZZ$ | | < 0.03 | < 0.03 | < 0.03 |
| $WZ$ | | < 0.10 | 0.21 | 0.21 |
| Background Sum | | 5.4 | 1.9 | 7.3 |

A data driven method is introduced for the background estimation. Control regions which are
**Figure 1.** Jet multiplicities in the same-sign dileptonic channel (top-left) and in the trileptonic channel (top-right); The transverse missing $E_T$ (MET), and the invariant mass of two opposite leptons, $M(\ell^+\ell^-)$. The open area represents the signal contributions assuming a $b'$ of 300 GeV/$c^2$, while the filled area shows the background contributions.

**Figure 2.** The distributions of $H_T$ for three signal $b'$ mass assumptions. The open histograms are the expected signal area for 300 GeV/$c^2$ $b'$ (left), 400 GeV/$c^2$ $b'$ (middle), and 500 GeV/$c^2$ $b'$ (right), and the filled histograms represent background events from various processes.
background rich are defined to normalize the background contributions. Events with two leptons of opposite charges are selected and all the other selection criteria are the same as for the signal regions. If at least two jets are required in the events it will help to cancel the systematics on the jet counting for the trilepton channel (which also requires \(N(\text{jets}) \geq 2\)). For the consideration of same-sign dilepton channel, the required minimum number of jets is four, in order to match the same \(N(\text{jets})\) requirement. The \(t\bar{t}\) background is expected to dominate in these regions.

The number of background \((N_B)\) and number of signal \((N_S)\) events in the signal region can be extracted by

\[
\begin{align*}
N_B &= N_B^{\text{control}} \times R_B = (N_S^{\text{control}} - N_S^{\text{control}}) \times R_B, \\
N_S &= N - N_B, \\
N_S^{\text{control}} &= N_S / R_S,
\end{align*}
\]

where \(N\) and \(N_S^{\text{control}}\) denote the total observed events in the signal region and in the control region. The ratio \(R_B\) (\(R_S\)) is the background (signal) ratio between the signal region and control region.

The background events usually come with a lepton with charge mis-identification, a fake lepton from jet, or a true lepton from \(b\)-jet. The major concern for the systematic uncertainties is on the background ratios (17%–124%) which are governed by the probability to observe a non-prompt lepton (lepton with charged mis-identification or lepton from \(b\)-jet) or a fake lepton in an event. The other dominant sources are the MET uncertainties (21%–30%) and jet energy scales (11%–27%). Systematic uncertainties are calculated for a cross-section measurement as well as the background contribution, assuming an early experimental condition.

The total systematic uncertainty on background yield is estimated to be \(+10.5_{-4.8}\) events and is included in the significance calculations. The results are shown in Table 1. With a small data set of 100 pb\(^{-1}\), we are already able to observe a \(b\bar{b}\) signal with a significance of 7.5\(\sigma\) if the \(b'\) mass is around 300 GeV/\(c^2\). The exclusion limits on the \(pp \rightarrow b\bar{b}'\) cross sections are estimated for a null hypothesis using Bayesian statistics. Using LO cross sections predictions as provided by Pythia, we are able to exclude the productions of \(pp \rightarrow b\bar{b}'\) up to a \(b'\) mass of 480 (420) GeV/\(c^2\) at the 95% confidence level with a data set of 100 (30) pb\(^{-1}\).

3. Analysis of heavy neutrino and the accompanying \(W_R\) boson
For the heavy neutrino searches, we chose the high energy electron triggers with thresholds 80 and 120 GeV. For muons we take isolated muon triggers.

Electrons and muons that are above a 20 GeV/\(c\) \(p_T\) threshold are first selected for a further study. The electron candidates are required to pass a cut-based identification. Rather loose criteria, \(\chi^2 < 10\) and \(N_{\text{hits}} > 7\), are applied for the muon candidates, which are reconstructed using both the CMS tracker and the muon chamber. These lepton candidates are required to have low tracking activities and low energy deposit in newery.

Jets are reconstructed by the iterative cone algorithm with a radius of 0.5. A standard algorithm that takes into account the different response of electromagnetic and hadronic showering is used to correct the jet energies. The minimum \(p_T\) for jet candidates is 40 GeV/\(c\) after the energy corrections. Furthermore, the jets with low charged tracks activities (\(\sum p_T^{\text{tracks}} / E_T^{\text{jet}} < 0.05\)) are removed from the analysis.

Signal candidates are preselected by requiring at least four reconstructed objects existing: two or more isolated leptons (of the same flavor but with any charge); at least one of them should has a \(p_T\) greater than 80 GeV/\(c\), and at least two jets. The invariant mass of the two leptons should at least be above 200 GeV/\(c^2\), for rejecting the contributions from the Dell-Yen process. The two highest \(p_T\) jets and the two isolated leptons are labeled by \(j_1, j_2\), and \(\ell_1, \ell_2\), while the subscript is the ordered by the \(p_T\) of the object. Using these objects, we reconstruct the following two variables:
• $M(N_\ell)_{\text{cand}}$, the invariant mass of the second lepton $\ell_2$, and the two jets, $j_1$ and $j_2$;
• $M(W_R)_{\text{cand}}$, the invariant mass of the selected four objects, $j_1$, $j_2$, $\ell_1$, and $\ell_2$.

These two kinematic variables for the signal events simulated at LRRP are shown in Figure 3. The tail in the distributions is due to the decay into $t$ quark ($N_\ell \rightarrow \ell W_R \rightarrow \ell tb$). There are more than two jets reconstructed in an event.

![Figure 3](image)

**Figure 3.** The invariant mass distributions, $M(W_R)_{\text{cand}}$ and $M(N_\ell)_{\text{cand}}$, for the events simulated with $M(W_R) = 2000$ GeV/$c^2$ and $M(N_\ell) = 500$ GeV/$c^2$.

We define a grand region ($M(W_R)_{\text{cand}} > 600$ GeV/$c^2$) and a two-dimensional peak region ($1250$ GeV/$c^2 < M(W_R)_{\text{cand}} < 1720$ GeV/$c^2$ and $480$ GeV/$c^2 < M(N_\ell)_{\text{cand}} < 710$ GeV/$c^2$) for benchmarking the performance of background rejection. The expected signal and background yields are shown in Table 2. The $t\bar{t}+\text{jets}$ production is one of the most important backgrounds of this study. The reconstructed mass distributions together with these Standard Model background processes are shown in Figure 4.

We factorize the reconstruction efficiencies as $\epsilon = \epsilon_{\text{trigger}} \cdot \epsilon_{\ell}^2 \cdot \epsilon_{j}^2$, where $\epsilon_{\text{trigger}}$ is the trigger efficiency, $\epsilon_{\ell}$ and $\epsilon_{j}$ are the lepton and jet reconstruction efficiency, respectively. The $\epsilon_{\ell}$ also includes the effect of the isolation requirement.

These efficiencies can mostly determined from data itself using a tag-and-probe method. For charged leptons, the $Z$ samples are used in such study. Applying the standard selection criteria only to one of the two leptons under the $Z$ peak (“tag”), and then ”probe” the accompanying lepton. This procedure is widely used in many other CMS studies as well. In particular, the influence of signal jets to the isolation performance is an important issue of this analysis.

Several cross section of the background processes are also carried out. The cross-flavor $e-\mu$ events are considered as a signal free control sample, assuming the mixing of different heavy neutrino flavors is tiny. This sample is mainly contributed by the $t\bar{t}$ events, and provide a cross-checks with the background shape predictions. As limited by the statistics at 100 pb$^{-1}$, only the projected distributions on the $M(N_\ell)_{\text{cand}}$ and $M(W_R)_{\text{cand}}$ can be compared.

The second important background component, $Z+\text{jets}$ events, could be examined by relaxing the $M_{\ell\ell}$ requirement to 80 GeV/$c^2$, which allows more $\gamma^*/Z+\text{jets}$ to contribute. A comparison between Monte Carlo predicted yield and distribution with these from the real data should provide useful information of $Z+\text{jets}$ process.

Furthermore, we should not thrust the absolute number of the predicted background yields, especially at the early experimental period. A fit on the two-dimensional $M(W_R)_{\text{cand}}-M(N_\ell)_{\text{cand}}$...
Table 2. Summary of expected signal and background yields for the search of heavy neutrinos and its accompany $W_R$ bosons. A dataset corresponding to $100 \text{ pb}^{-1}$ integrated luminosity is assumed. The signal events in this table is generated at $M(W_R) = 1.5 \text{ TeV}/c^2$ and $M(N_\ell) = 500 \text{ GeV}/c^2$.

| Process       | Electron Channel | Muon Channel |
|---------------|------------------|--------------|
|               | Grand Reg. 2D Peak Reg. | Grand Reg. 2D Peak Reg. |
| Signal        | 23 14            | 23 17.6      |
| $t\bar{t}$+jets | 19 0.44          | 22 0.57      |
| Z+jets        | 7.2 0.15         | 8.7 0.16     |
| W+jets        | 2.1 0.31         | 0.025 0      |
| $\gamma$+jets | 0.68 0           | 0 0          |
| QCD           | 0.23 0           | 3.4 0        |
| $WW$          | 2.27 0.084       | 2.6 0.19     |
| $WZ$          | 0.56 0           | 0.57 0       |
| Others        | 0.85 0.1         | 0.32 0       |
| Background Sum | 5.4 1.9         | 7.3          |

Figure 4. The reconstructed mass distributions, $M(W_R)^{\text{cand}}$ and $M(N_\ell)^{\text{cand}}$, with background distributions from Standard Model processes. The signal is generated at LRRP1. These distributions are normalized to a $100 \text{ pb}^{-1}$ data set.

distribution is introduced to extract the signal yields. The probability density function of the fit is given by

$$ P(M(W_R)^{\text{cand}}, M(N_\ell)^{\text{cand}}) = N_S \times BW(\mu(W_R), \Gamma(W_R), M(W_R)^{\text{cand}}) \times BW(\mu(N_\ell), \Gamma(N_\ell), M(N_\ell)^{\text{cand}}) + $$
\[ N_B \times P_B(M(W_R)^{\text{cand}}, M(N_\ell)^{\text{cand}}), \]  

where \( BW(\mu, \Gamma, M^{\text{cand}}) \) is a Breit-Wigner function, \( P_B \) is the shape of the background which is modeled by a smoothed histogram based on the results of Monte Carlo simulations. The number of signal events \( (N_S) \), the mean values of the signal peak \( (\mu(W_R) \) and \( \mu(N_\ell) \), and the number of background events \( (N_B) \) are free in the fit. The width of the signal distributions, \( \Gamma(W_R) \) and \( \Gamma(N_\ell) \), are quasi-free in the fit. Instead of simply fixed in the fit, they are constrained to be close to the values obtained simulations.

The initial distributions obtained from the simulations of signal and background events for a 100 pb\(^{-1}\) data sample are shown in Figures 5. It is clear that the model well describes the Monte Carlo samples.

![Figure 5](image_url)  

**Figure 5.** The initial distributions from weighted events of the signal and background Monte Carlo samples (left); the plot of the probability density function obtained from fit (right).

Finally, we construct our 5\( \sigma \) discovery contours in the \( (M(W_R); M(N_\ell)) \) plane are obtained using the signal samples simulated different \( M(W_R) \) and \( M(N_\ell) \) in the range of 1000 GeV/c\(^2\) \(< M(W_R) < 2000 \text{ GeV}/c^2, \) 300 GeV/c\(^2\) \(< M(N_\ell) < 1600 \text{ GeV}/c^2. \) The discovery contour for the electron channel is shown in Figure 6. The contour for the muon channel is slightly wider, but the difference is small since the cross sections do drop rapidly for higher masses. The limits at 95% confidence level on the heavy neutrino signales are also given in the same figure. In the limit estimations, we apply an extra smearing to accommodate the systematic uncertainties.

In conclusion, we have studied the CMS discovery potential for a heavy right-handed neutrino \( N_\ell (\ell = e, \mu) \) and the accompanying heavy \( W_R \) gauge boson that may appear in the minimal left-right symmetric model. By requiring the final state consistent with two leptons and two jets, a good separation of the signal from the background processes is achieved. Based on a data sample of 100 pb\(^{-1}\), these new particles can be observed at the level of 5\( \sigma \) in the mass region up to \( M(W_R) = 2100 \text{ GeV}/c^2 \) and \( M(N_\ell) = 1200 \text{ GeV}/c^2. \)

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Figure 6. The $5\sigma$ discovery potential of the $W_R$ boson and right-handed neutrinos from the left-right symmetric model in the electron channel, and the exclusion contour at 95% confidence level. An integrated luminosity of 100 pb$^{-1}$ collected at 14 TeV recorded by the CMS detector is assumed in this study. The horizontal line are exclusion limit given by the LEP experiment.

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