Discovering the 4th Generation

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Abstract

In this report we have studied the signatures of an additional fourth generation of heavy leptons and how they would look like at the LHC. In order to study this we used the CalcHEP program where we added new particles and interactions according to predictions from theory. In order to validate our implementations we cross checked the output from CalcHEP with analytical expressions of decay width. Further we looked at final states with same sign leptons together with jets. These are interesting final states for searches at the LHC since same sign dilepton production in the Standard Model is believed to be very small. Finally we used a full 4th generation model within the Minimal Walking Technicolor framework and looked at some interesting signals which could serve as good candles in order to discover such kind of models at a hadron collider. If models, like the one we have studied here, are realized in nature, LHC will be able to discover them or at least set hard limits on the masses and couplings.

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1 Theory

All the Standard Model fermions are Dirac-type fermions except for the neutrino, whose nature is not yet determined. A Dirac fermion is defined by:

$$\Psi_D = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \tag{1}$$

where ψ_L and ψ_R are Weyl spinors of opposite chirality. Charge conjugation allows to write a new Dirac spinor, defined by:

$$\Psi^c = -i \begin{pmatrix} 0 & \sigma^2 \\ -\sigma^2 & 0 \end{pmatrix} \Psi^* = \begin{pmatrix} -i\sigma^2\psi_R^* \\ i\sigma^2\psi_L^* \end{pmatrix} \tag{2}$$

In general Ψ^c is different from Ψ, meaning that a Dirac-type particle is different from its antiparticle. If the fermion is electrically neutral, like the neutrino, it could coincide with its own antiparticle. In that case it would be described by a Majorana spinor which satisfies the following condition:

$$\Psi_M^c = \Psi_M \tag{3}$$

To satisfy this condition ψ_R cannot be independent from ψ_L, namely:

$$\psi_R = i\sigma^2\psi_L^* \longrightarrow \Psi_M = \begin{pmatrix} \psi_L \\ i\sigma^2\psi_L^* \end{pmatrix} \tag{4}$$

The mass term for a Dirac fermion is:

$$\mathcal{L} \supset -m\bar{\Psi}_D\Psi_D = -m(\psi_L^\dagger\psi_R + h.c.) \tag{5}$$

A Majorana mass term would look the same except that ψ_R is not an independent spinor:

$$\mathcal{L} \supset m(i\psi_L^T\sigma^2\psi_L + h.c.) \tag{6}$$

Under a $U(1)$ transformation a Dirac fermion would transform like:

$$\begin{matrix} \psi_L \to \psi_L e^{i\alpha} \\ \psi_R \to \psi_R e^{i\alpha} \end{matrix} \Rightarrow \Psi_D \to \Psi_D e^{i\alpha} \tag{7}$$

while a Majorana spinor does not transform with a global phase since the left and right components are not independent:

$$\begin{matrix} \psi_L \to \psi_L e^{i\alpha} \\ \psi_R \to \psi_R e^{-i\alpha} \end{matrix} \tag{8}$$

This implies that a massive Majorana fermion can not carry any conserved $U(1)$ charge, like electric charge or lepton number. Actually, even if it is a massless Majorana particle a process like:

$$Z \to \nu\bar{\nu} \tag{9}$$

would violate lepton number.
We know from neutrino oscillation evidence that they have a mass and we have different possibilities:

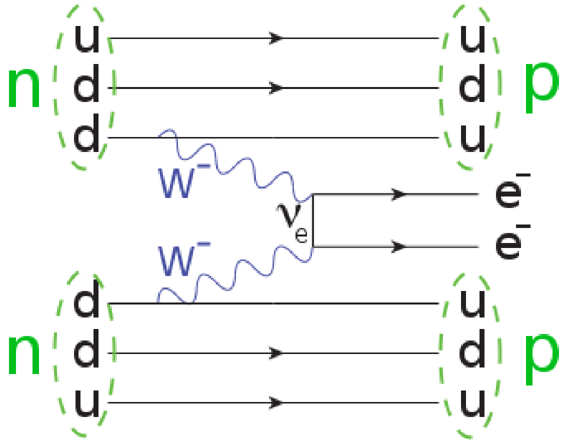


Figure 1: Tree level Feynman diagram for neutrino-less double beta decay.

- Dirac neutrino: in this case we need a right-handed component which has to be not charged under the Standard Model gauge group. A Dirac-type mass term would conserve lepton number.
- Majorana neutrino: in this case we don't need any additional field, but we would violate lepton number conservation.
- We could also introduce a sterile neutrino and at the same time give it a Majorana-type mass and, mixing it with the normal neutrino, give it a Dirac-type mass. In this case again we would violate lepton number.

One possibility to unveil the nature of neutrino is looking for the neutrino-less double beta decay **??**, which violates lepton number. The observation of this process would point towards a Majorana-type neutrino.
In this project we tried to understand experimental signatures of Majorana particles by using CalcHEP. In particular we could add a fourth generation of leptons to the Standard Model, consisting of:

$$L_\xi = (\nu_{\xi L}, \xi_L)^T \sim (1, 2, -1/2) \quad \xi_R \sim (1, 1, -1) \quad \nu_{\xi R} \sim (1, 1, 0) \tag{10}$$

and give both Majorana and Dirac masses to the new neutrino. If then we allow for mixing with one generation of standard neutrinos diagonalization of mass matrix would lead to three Majorana eigenstates and the couplings of the new states to the standard leptons will depend on the mixing angles. In the first part we actually considered a simplified model by adding two Majorana neutrinos to the Standard Model and coupling them to electrons and gauge bosons just in the same way as normal neutrinos ignoring mixing angles. This is just a toy model used to examine experimental signatures from processes similar to neutrino-less double beta decay. In the last part we examined also a more realistic fourth generation model based on Minimal Walking Technicolor theory.

2 Implementation

2.1 Validation

WARNING; In CalcHEP remember to put Force Unitary gauge on !

In CalcHEP, we want to observe the interaction of a heavy Majorana neutrino with the W and Z bosons. Therefore we need to introduce two additional particles to CalcHEP : massive Majorana neutrino and massless Majorana neutrino. In order to do that, we need to add new particles to the Standard Model Particles section, fix their masses in Parameters section and introduce their vertices in Vertices section. To implement the vertices, we use equation (11), (12) and (13).

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \left(\bar{\ell}\gamma^\mu V_{\ell N} P_L N \; W_\mu + \bar{N}\gamma^\mu V_{\ell N}^* P_L \ell \; W_\mu^\dagger \right) . \tag{11}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \left(\bar{\nu}_\ell \gamma^\mu V_{\ell N} P_L N + \bar{N}\gamma^\mu V_{\ell N}^* P_L \nu_\ell \right) Z_\mu . \tag{12}$$

$$\mathcal{L}_Z = -\frac{g}{2c_W} \, \bar{\nu}_\ell \gamma^\mu \left(V_{\ell N} P_L - V_{\ell N}^* P_R \right) N \; Z_\mu \qquad (\nu_\ell, N \text{ both Majorana}) \tag{13}$$

with $P_L \equiv (1-\gamma_5)/2$ for l and $P_L \equiv (1+\gamma_5)/2$ for ν_l. For simplicity we only looked at the electron channel, i.e. putting $V_{\mu N} = V_{\tau N} = 0$ and $V_{eN} = 1$. In order to validate our implementations we compared the width for some selected decays between CalcHEP and the analytic expression shown in equation (14). The results are summarized in table 1

$$\begin{aligned}
\Gamma(N \to W^+ \ell^-) &= \Gamma(N \to W^- \ell^+) \\
&= \frac{g^2}{64\pi} |V_{\ell N}|^2 \frac{m_N^3}{M_W^2} \left(1 - \frac{M_W^2}{m_N^2}\right) \left(1 + \frac{M_W^2}{m_N^2} - 2\frac{M_W^4}{m_N^4}\right) , \\
\Gamma_D(N \to Z\nu_\ell) &= \frac{g^2}{128\pi c_W^2} |V_{\ell N}|^2 \frac{m_N^3}{M_Z^2} \left(1 - \frac{M_Z^2}{m_N^2}\right) \left(1 + \frac{M_Z^2}{m_N^2} - 2\frac{M_Z^4}{m_N^4}\right) , \\
\Gamma_M(N \to Z\nu_\ell) &= 2\,\Gamma_D(N \to Z\nu_\ell) ,
\end{aligned} \tag{14}$$

Width	CalcHEP [GeV]	Calculated [GeV]
Γ	8.793	8.793
Γ_D	4.354	4.353
Γ_N	8.708	8.707

Table 1: Calculated with compared with the results from CalcHEP.

2.2 Phenomenology

An important experimental signature for the discovery of Majorana fermions would be to have two same sign leptons in the final state (like in figure 2) since this channel has low Standard Model background. By using CalcHEP we can estimate the cross section of such final state as the function of the invariant mass of the two jets and one of the electrons. Figure 3 and 4 shows these results. In figure 3(a) we've used the highest p_T electron and in 3(b) we've used the lowest p_T electron in the calculation. As expected we see that the in figure 3(a) the cross section is larger for high mass and vice versa in figure 3(b). We also a peak around the mass of the Majorana neutrino, as expected. In figure 4 we've plotted the sum of the two histograms in 3.

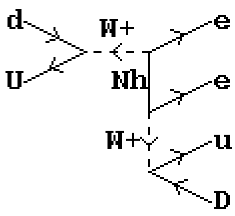
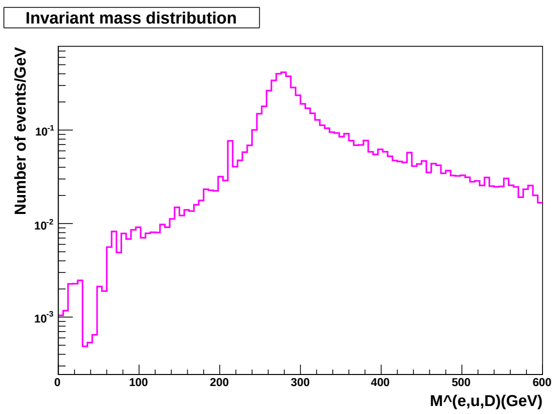
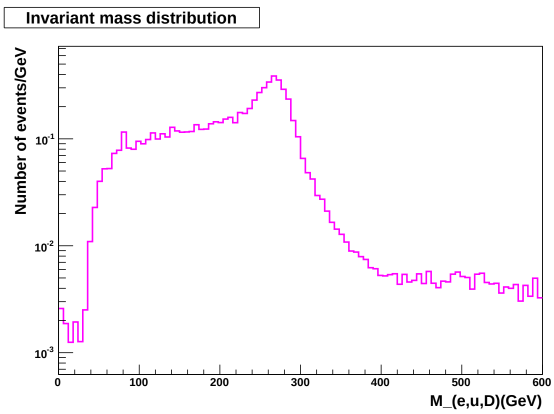


Figure 2: Feynman diagram of a process giving two same sign electrons in the final state.



(a) using the highest p_T electron



(b) using the lowest p_T electron

Figure 3: Invariant mass of $e\, u\, \bar{d}$

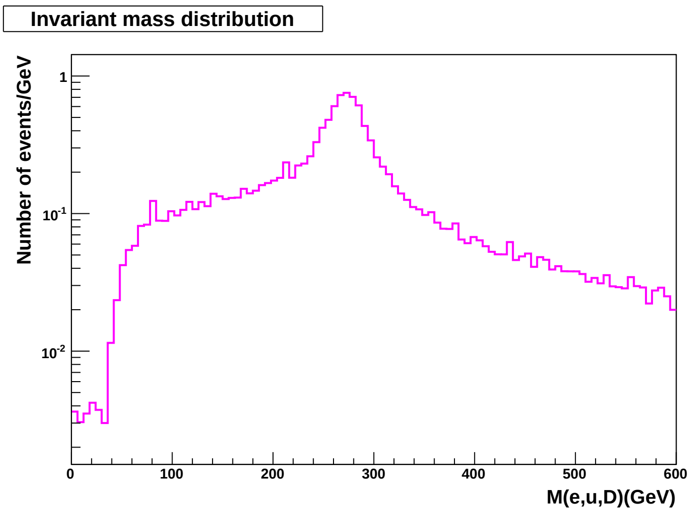


Figure 4: Invariant mass of $e\,u\,\bar{d}$ using the sum of the histograms in 3

3 4th Generation Leptons from the Minimal Walking Technicolor

3.1 Introduction

Electroweak symmetry breaking can be obtained in a number of ways, most notably via the famous Higgs mechanism. However, QCD already includes an electroweak symmetry breaking mechanism through the quark condensate $< \bar{u}_L u_R + \bar{d}_L d_R > \neq 0$. The mass given to the vector bosons from this mechanism is much lower than the experimentally observed values, and the mechanism is therefore insufficient. Inspired by this, it has been proposed to add an additional QCD-like gauge symmetry group to that of the Standard Model leading to what are called Technicolor models.

The first naïve Technicolor models have proven to be in contradiction with the electroweak precision constraints and have therefore been discarded as complete models of Nature. We will in this section consider a very interesting model known as Minimal Walking Technicolor which is a serious candidate for electroweak symmetry breaking. Its most notable features are the slowly running, or walking, coupling constant and a fourth generation of leptons as seen in table 2 that cancel the Witten anomaly.

$\xi^{\pm}$	Electron/positron-like particle.
$N_{0,1,2}$	Heavy Majorana neutrinos.
$R_{1,2}^{0,\pm}$	Heavy vector technimesons.

Table 2: List of new particles in MWT relevant to this report plus the fourth lepton generation [1].

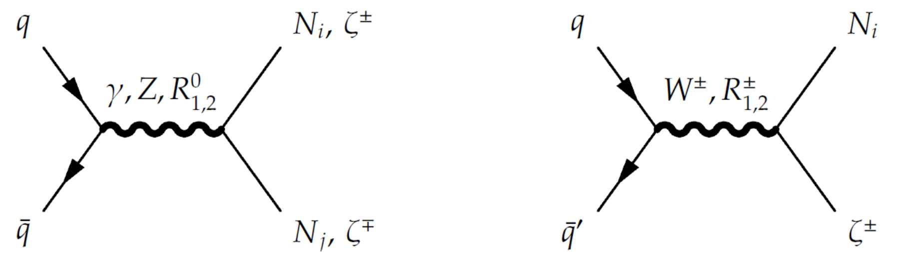


Figure 5: The tree-level Feynman diagrams that produce the fourth generation leptons, $i, j = 1, 2$ [1].

3.2 Phenomenology

When looking for evidence that Technicolor models describe Nature in hadron colliders, it is very important to have distinct signature. One such is that the the production of a possible fourth generation of leptons would be greatly enhanced, as seen in figure 6. It is very important to realize that the two distinct peaks will only be present if the fourth generation couples to vector mesons, such as the ones found in Technicolor models [1]. Had the fourth generation been the result of a sequential extension of the Standard Model, they would not be present.

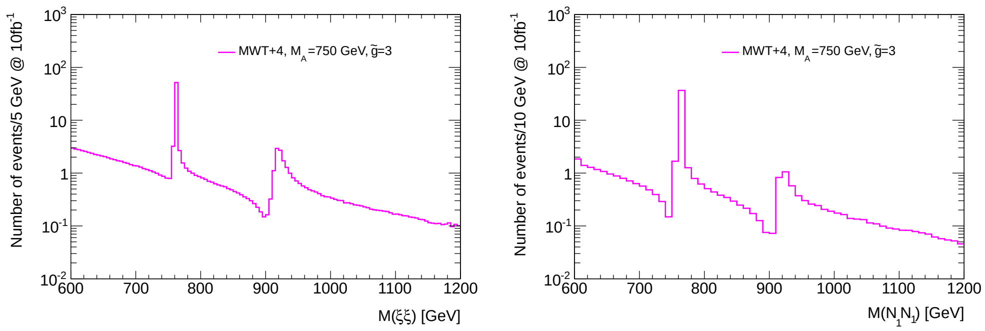


Figure 6: The signature of the fourth generation leptons resulting from the left-hand Feynman diagram in figure 5.

3.3 Calculating the process in CalcHEP

We imported the CalcHEP model file developed in section 5.3 of [1] with the additional particles and vertices relevant to seeing the signature of a fourth lepton generation in a hadron collider. Using CalcHEP's automated event generation, we computed the distribution of the invariant masses of pairs of fourth generation leptons generated in a p-p -collision at $\sqrt{s} = 7TeV$.

References

[1] J. R. Andersen, O. Antipin, G. Azuelos, L. Del Debbio, E. Del Nobile, S. Di Chiara, T. Hapola, M. Jarvinen *et al.*, "Discovering Technicolor," [arXiv:1104.1255 [hep-ph]].