Chapter 5

Color Octet Electrons at the LHC

In this chapter we study the LHC discovery potential for a generic color octet partner of charged lepton, namely the color octet electron, $e_8$. Although, here we consider only the $e_8$, our results are applicable for the color octet partner of muon, i.e., $\mu_8$ also. In Sec. 5.1 we briefly discuss some preonic models of quark-lepton compositeness in which $e_8$’s are present. In Sec. 5.2 we display the interaction Lagrangian of a generic $e_8$ and compute its decay width. In Sec. 5.3 we explore different production (including pair and single) channels of $e_8$’s in the context of the LHC. We have identified a new set of single production diagrams whose contribution is comparable to other dominant production channels of the $e_8$. A common feature in all the resonant production channels of the $e_8$ is the presence of two high-$p_T$ electrons and at least one high-$p_T$ jet in the final state. Using this feature, we implement a search method where the signal is a combination of pair and single production events. In Sec. 5.4 we compute the LHC reach for $e_8$ using this combined events. We show that this method has potential to increase the LHC reach significantly. We have also used our method to set limit on the compositeness scale.
5.1 Preon models of compositeness

In this section we present some motivating examples of preon models of composite leptons in which color octet leptons are present. These models assume that the SM particles may not be fundamental, and just as the proton has constituent quarks, they are actually bound states of substructural constituents called preons [70]. These constituents are visible only beyond a certain energy scale known as the compositeness scale. A typical consequence of quark-lepton compositeness is the appearance of colored particles with nonzero lepton numbers (leptoglouns, leptoquarks) and excited leptons etc. Some composite models naturally predict the existence of color octet fermions with nonzero lepton numbers [70–76]. It is assumed that preons are either fermion or scalar and they are color triplet under $SU(3)_c$. Here we describe two preonic models just to show how color octet lepton arises in compositeness models of leptons.

**Fermion-scalar model:** In the fermion-scalar models [75, 129–131], leptons are bound states of one fermionic preon ($F$) and one scalar anti-preon ($\bar{S}$), and quarks are bound states of one fermionic anti-preon ($\bar{F}$) and one scalar anti-preon. In group theoretic language, color decomposition of the tensor product of one color triplet and one color anti-triplet can be written as

\[
\ell = (F \bar{S}) \equiv 3 \otimes \bar{3} \equiv 1 \oplus 8 \\
q = (\bar{F} \bar{S}) \equiv \bar{3} \otimes \bar{3} \equiv 3 \oplus \bar{6} .
\]  

(5.1)

**Three-Fermion model:** In the three fermion models [73, 74], leptons are assumed to be a bound state of three fermionic preons, and quarks are bound states of two fermionic preons and one fermionic anti-preon. The color decomposition of the tensor products of
three color triplets can be written as

\[ \ell = (FFF) \equiv 3 \otimes 3 \otimes 3 \equiv 1 \oplus 8 \oplus 8 \oplus 10 \]
\[ q = (F\bar{F}F) \equiv 3 \otimes \bar{3} \otimes 3 \equiv 3 \oplus \bar{3} \oplus 6 \oplus 15 \]  \hspace{1cm} (5.2)

In the above two decompositions of lepton, we identify “1” as the SM lepton and the “8” as the color octet partner of the SM lepton. In the “three-fermion” model “10” is the decouplet partner of the SM lepton. Similarly, we identify “3” as the SM quark and “\bar{3}”, “\bar{6}” and “15” as the exotic partners of the SM quarks. The full \( SU(2)_L \otimes U(1)_Y \) structure of the preonic models can be found in Refs. [73–75, 129–131]. In this thesis we restrict ourselves in the lepton sector, in particular we focus on the LHC phenomenology of \( \epsilon_8 \) in a model independent fashion.

5.2 The Lagrangian of \( \epsilon_8 \)

We write the Lagrangian of \( \epsilon_8 \) in a model independent manner. Assuming lepton flavor conservation, we consider a general Lagrangian for the \( \epsilon_8 \) including terms allowed by the gauge symmetries of the SM,

\[ \mathcal{L} = \bar{\epsilon}_8^a \gamma^\mu (\partial_\mu \delta^{ac} + g_s f^{abc} G^b_\mu) \epsilon_8^c - M_\epsilon \bar{\epsilon}_8 \epsilon_8 + \mathcal{L}_{\text{int}} \]  \hspace{1cm} (5.3)

In this thesis, we have ignored the interaction terms of the color octet partners of neutrinos and also all the terms involving electroweak interactions. Presence of these interactions could potentially affect the EWPT observables and experimental limits on those observables can be used to indirectly constraint the theory. But, in this thesis we are more interested to probe \( \epsilon_8 \) directly at the LHC in a model independent way. Therefore, we focus on the dominant lowest dimensional interactions which are relevant for the production of \( \epsilon_8 \) at the LHC. The interaction part (\( \mathcal{L}_{\text{int}} \)) contains all the higher-dimensional operators. We consider only the following dominant mass dimension-5 terms that contain
the interactions between the SM electrons and the color octet ones [88] and neglect all the higher dimensional (dimension-6 and above) interactions \(^1\),

\[
\mathcal{L}_{\text{int}} = \frac{g_s}{2\Lambda} G^a_{\mu\nu} \left[ \varepsilon_8^a \sigma^{\mu\nu} (\eta_L e_L + \eta_R e_R) \right] + \text{H.c. .} \tag{5.4}
\]

Here \(G^a_{\mu\nu}\) is the gluon field strength tensor, \(\Lambda\) is the scale below which this effective theory is valid and \(\eta_{L/R}\) are the left/right couplings. Chirality conservation implies the product of \(\eta_L\) and \(\eta_R\) should be zero [88], and therefore we assume \(\eta_L = 1\) and \(\eta_R = 0\) in our analysis.

![Diagram](image)

**Figure 5.1:** Decay width of \(e_8\) as functions of \(M_{e_8}\) for \(\Lambda = M_{e_8}\) and \(\Lambda = 5\) TeV.

From the interaction Lagrangian given in Eq. (5.4) we see that an \(e_8\) can decay to a gluon and an electron (two-body decay mode), \(i.e., e_8 \rightarrow e g\). With \(\eta_L = 1\) and \(\eta_R = 0\), the decay width of \(e_8\) can be written as,

\[
\Gamma_{e_8} = \frac{\alpha_s(M_{e_8}) M_{e_8}^3}{4\Lambda^2} , \tag{5.5}
\]

In Fig. 5.1 we show the decay width of \(e_8\) as functions of \(M_{e_8}\) with \(\Lambda = M_{e_8}\) and \(\Lambda = 5\) TeV.

\(^1\)There are actually more dimension five operators allowed by the gauge symmetries and lepton number conservation like,

\[
\frac{C_8}{\Lambda} f^{abc} e_8^a G^b_{\mu\nu} \sigma^{\mu\nu} e_8^c + \frac{C_1}{\Lambda} e_8^a B_{\mu\nu} \sigma^{\mu\nu} e_8^a .
\]

These terms lead to momentum dependent \(e_8 e_8 g g\) vertices (form factors). Moreover, the octet term can lead to a \(e_8 e_8 g g\) vertex which can affect the production c.s. We assume the unknown coefficients associated with these terms are negligible.

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5.3 Production at the LHC

In this section we discuss various production mechanisms of $e_8$’s at the LHC and present the production c.s. for different channels. To obtain the c.s., we have implemented the Lagrangian of Eq. (5.3) in FeynRules version 1.6.0 [132] to generate Universal FeynRules Output (UFO) [133] format model files suitable for MadGraph5 [134] that we have used to compute c.s. We have used CTEQ6L PDFs [115] for all our numerical computations.

At a hadron collider like the LHC, resonant productions of $e_8$’s can occur via $gg$, $gq$ and $qq$ initiated processes where $q$ can be either a light quark or a bottom quark. For the resonant production $e_8$’s at colliders, two separate channels are generally considered in the literature – one is the pair production [84,85] and the other is the single production of $e_8$ [80–83,86]. In general, pair production of a colored particle is considered mostly model independent. This is because the universal strong coupling constant $g_s$ controls the dominant pair production processes unlike the single production processes where the c.s. depends more on various model parameters like couplings and scales etc. However, as we shall see, for $e_8$’s, the $t$-channel electron exchange diagrams can contribute significantly to the pair production making it more model dependent.

5.3.1 Pair Production ($gg, qq \rightarrow e_8e_8$)

![Feynman diagrams](image)

Figure 5.2: Parton level Feynman diagrams for $pp \rightarrow e_8e_8$ process at the LHC.

At the LHC, pair production of $e_8$’s is $gg$ or $qq$ initiated, see Fig. 5.2 where we have shown the parton level Feynman diagrams for this channel. Of these, only the electron
Figure 5.3: The c.s. for $pp \to e_8e_8$ as functions of $M_{e_8}$ for $\Lambda = M_{e_8}$ and $\Lambda = 5$ TeV at the 14 TeV LHC.

Figure 5.4: Dependence of $\delta \sigma/\sigma$ (defined in Eq. (5.6)) on $M_{e_8}/\Lambda$ for $M_{e_8} = 1$ TeV and 2 TeV at the 14 TeV LHC.

exchange diagram, shown in Fig. 5.2(d), contains the $\Lambda$ dependent $g ee_8$ vertex. In Fig. 5.3 we show the $pp \to e_8e_8$ c.s. as functions of $M_{e_8}$ for two different choices of $\Lambda$, $\Lambda = M_{e_8}$ and $\Lambda = 5$ TeV, at the 14 TeV LHC. In Fig. 5.4 we have plotted $\delta \sigma$ as functions of $\Lambda$ to show the dependence of the pair production c.s. on $\Lambda$ for $M_{e_8} = 1$ and 2 TeV, where $\delta \sigma$ is a measure of the contribution of the electron exchange diagram and is defined as,

$$\delta \sigma(\Lambda) = \sigma(\Lambda) - \sigma(\Lambda \to \infty) \, . \tag{5.6}$$
As $\Lambda$ increases the contribution coming from the electron exchange diagrams decreases and for $\Lambda \gg M_{e8}$ becomes negligible. So the pair production is model independent only for very large $\Lambda$. After being pair produced at the LHC, each $e_8$ decays into an electron (or a positron) and a gluon at the parton level, i.e., $gg/qq \to e_8e_8 \to eejj$. For large $M_{e8}$, these two jets and the lepton pair will have high-$p_T$. This feature can be used to isolate the $e_8$ pair production events from the SM backgrounds at the LHC.

### 5.3.2 Two-body Single Production ($gg, qq \to e_8e$)

![Feynman diagrams](image)

Figure 5.5: Parton level Feynman diagrams for $pp \to e_8e$ process at the LHC.

![Graph](image)

Figure 5.6: The c.s. for $pp \to e_8e$ as functions of $M_{e8}$ for $\Lambda = M_{e8}$, 5 TeV and 10 TeV at the 14 TeV LHC.

The two-body single production channel where an $e_8$ is produced in association with an electron can have either $gg$ or $qq$ initial states as shown in Fig. 5.5. This channel is model dependent as each Feynman diagram for the $pp \to e_8e$ process contains a $\Lambda$
dependent vertex. In Fig. 5.6 we show the $pp \to e_8 e$ c.s. as functions of $M_{e_8}$ with $\Lambda = M_{e_8}$ and 5 TeV and 10 TeV at the 14 TeV LHC. As the $e_8$ decays, this process gives rise to a $eej$ final state at the parton level. The $e$ and the $j$ produced from the decay of the $e_8$, have high-$p_T$. The other $e$ also possesses very high-$p_T$ as it balances against the massive $e_8$.

### 5.3.3 Three-body Single Production ($gg, gq, qq \to e_8 ej$)

Apart from the pair and the two-body single productions, we also consider single production of an $e_8$ in association with an electron and a jet. The $pp \to e_8 ej$ process includes three different types of diagrams as follows:

1. The diagrams where the $ej$ pair is coming from another $e_8$. Though there are three particles in the final state, this type of diagram effectively corresponds to two body pair production process.

2. The two body single production ($pp \to e_8 e$) process with a jet radiated from initial state (ISR) or final state (FSR) or intermediate virtual particles can lead to an $e_8 ej$ final state.

3. A new set of diagrams that are different from the two types of diagrams mentioned above. These new channels can proceed through $gg$, $qq$ and $gq$ initial states as shown in Fig. 5.7.

This new set of diagrams has not been considered so far in the literature. It is difficult to compute the total contribution of these diagrams in a straight forward manner with a leading order parton level matrix element calculation because of the presence of soft radiation jet emission diagrams. In order to get an estimation of the contribution of these new diagrams without getting into the complicacy of evaluating the soft jet emission diagrams, here, in this section, we present the c.s. only for the $gq$ initiated processes, i.e. $gq \to e_8 ej$ since the first and the second types of diagrams of $pp \to e_8 ej$ process can not
be initiated by $gq$ state. In Fig. 5.9 we show the c.s. of the $gq \rightarrow e_8 ej$ process along with the $pp \rightarrow e_8 e$ and the $pp \rightarrow e_8 e$ processes. We find that the c.s. even for the $gq$ initiated subset can be comparable to the $pp \rightarrow e_8 e_8 / e_8 e$ processes for large $M_{e_8}$ despite the facts that these new diagrams have three-body final states and are suppressed by one extra power of the coupling (either $g_s$ or $g_s/\Lambda$) compared to the two-body single and pair production processes. However, since there is one less $e_8$ compared to the pair production process, depending on the coupling the three-body phase space of the single production can be comparable or even larger to the two-body phase space of the pair production for large $M_{e_8}$. After the $e_8$ decay, the three-body single production process is characterized by an $eejj$ final state like the pair production. However, unlike the pair production, here one of the jet can have a low transverse momentum most of the time.
5.3.4 Indirect Production ($gg \to ee$)

So far we have considered only resonant production of $e_8$’s. However, a t-channel exchange of the $e_8$ can convert a gluon pair to an electron-positron pair at the LHC (Fig. 5.8). Similar indirect productions in the context of the future linear colliders such as the ILC and CLiC have been analyzed in [87]. Indirect production is less significant because the amplitude is proportional to $1/\Lambda^2$. Moreover, at the LHC this is also color suppressed because of the color singlet nature of the final states. In Fig. 5.9 we also show the c.s. of the indirect production process at the LHC.

5.4 LHC Discovery Potential

From Fig. 5.9 we see that for small $M_{e_8}$, the pair production c.s. is larger than the other channels. As $M_{e_8}$ increases, it decreases rapidly due to phase-space suppression
and the single production channels (both the two-body and the three-body) take over
the pair production (the crossover point depends on $\Lambda$). Hence, if $\Lambda$ is not too high,
the single production channels will have better reach than the pair production channel
and so, to estimate the LHC discovery reach, we consider both the pair and the single
production channels. However, while estimating for the single production channels we
have to remember that because of the radiation jets, it will be difficult to separate the two-
body and the three-body single productions at the LHC. So, in this paper, we consider a
selection criterion that combines events from all the production processes at the LHC.

5.4.1 Combined Signal

To design the selection criterion mentioned above we first note some of the characteristics
of the final states of the resonant production processes $^2$,

1. Process $pp \rightarrow e_8 e_8 \rightarrow (eg)(eg)$ has two high-$p_T$ electrons and two high-$p_T$ jets in
the final state.

2. Process $pp \rightarrow e_8 e \rightarrow (eg)e$ has two high-$p_T$ electrons and one high-$p_T$ jet in the
final state.

3. Process $pp \rightarrow e_8 e j \rightarrow (eg)ej$ has two high-$p_T$ electrons and at least one high-$p_T$ jet
in the final state.

All these processes have one common feature that they have two high-$p_T$ electrons
and a high-$p_T$ jet in the final state. Hence, if we demand that the signal events should
have two high-$p_T$ electrons and at least one high-$p_T$ jet, we can capture events from all
the above mentioned production processes. To estimate the number of signal events that
pass the above selection criterion we combine the events from all the production channels
mentioned in the previous section. However, as already pointed out, it is difficult to

$^2$We focus on the resonant productions because as we saw the indirect production is less significant
at the LHC.
computation due to the presence of soft radiation jets. Hence, we use the MadGraph ME
generator to compute the hard part of the amplitude and Pythia6 (via the MadGraph5-
Pythia6 interface) for parton showering. We also match the matrix element partons with
the parton showers to estimate the inclusive signal without double counting (see the
Appendix B for more details on the matched signal).

5.4.2 SM Backgrounds

With the selection criterion mentioned in the previous section to capture all the contribu-
tions from different production channels, the SM backgrounds are characterized by the
presence of two opposite-sign electrons and at least one jet in the final state. At the LHC,
the main source of $e^+e^-$ pairs (with high-$p_T$) is the $Z$ decay \(^3\). Hence, we compute the
inclusive $Z$ production as the main background. Here, too, we compute this by matching
of matrix element partons of $Z + n$ jets ($n = 0, 1, 2, 3$) processes\(^4\) with the parton showers
using the shower-$k_T$ scheme [135]. For the background, we also consider some potentially
significant processes to produce $e^+e^-$ pairs,

\[
pp \rightarrow tt \rightarrow (bW)(bW) \rightarrow (be\nu_e)(be\nu_e) ,
\]

\[
pp \rightarrow tW \rightarrow bWW \rightarrow (be\nu_e)(e\nu_e) ,
\]

\[
pp \rightarrow WW \rightarrow (e\nu_e)(e\nu_e) .
\]

Note that all these processes have missing energy because of the $\nu_e$’s in the final state. In
Table 5.1 we show the relative contributions of these backgrounds generated with some
basic kinematical cuts (to be described shortly) on the final states. As mentioned, we see
in Table 5.1 that the inclusive $Z$ contribution overwhelms the other background processes.

\(^3\)Here we do not include $e^+e^-$ pairs that come from $\gamma^*$. However, as we shall demand very high-$p_T$
for both the electrons, this background becomes negligible and would not affect our results too much.

\(^4\)Here $pp \rightarrow Zjj$ includes the processes where the jets are coming from a $W$ or a $Z$. 

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<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + nj$</td>
<td>$2.11E4$</td>
</tr>
<tr>
<td>$tt$</td>
<td>$1.95E3$</td>
</tr>
<tr>
<td>$tW$</td>
<td>$132.15$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$7.51$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.32E4$</td>
</tr>
</tbody>
</table>

Table 5.1: The main SM backgrounds for the combined production of $e_8$’s obtained after applying the Basic cuts (see text for definition) at the 14 TeV LHC.

### 5.4.3 Kinematical Cuts

![Graphs showing distributions for different processes](image)

Figure 5.10: Comparison between various distributions for the combined signal with $M_{e_8} = 2$ TeV ($\Lambda = 5$ TeV) and the inclusive $Z$ background for the 14 TeV LHC. The inclusive $Z$ background is scaled by a factor of $10^4$.

In Fig. 5.10(a) we display the $p_T$ distributions of $e$’s from the combined signal and the inclusive $Z$ production, respectively. For the signal, we have chosen $M_{e_8} = 2$ TeV and $\Lambda = 5$ TeV. As expected, the distribution for the $e$ coming from the background has a
peak about \( M_Z/2 \) but there is no such peak for the signal. We can also see the difference between the \( p_T \) distributions of the leading \( p_T \) jets for the signal and the background in Fig. 5.10(b). We also display the distributions of \( M(e^+, e^-) \) in Fig. 5.10(c) and \( M(e^-, j_1) \) in Fig. 5.10(d) (where \( j_1 \) denotes the leading \( p_T \) jet) which show very different shapes for the signal and the background. Motivated by these distributions we construct some kinematical cuts to separate the signal from the background.

1. **Basic cuts**

   For \( x, y = e^+, e^-, j_1, j_2 \) (\( j_1 \) and \( j_2 \) denote the first two of the \( p_T \)-ordered jets respectively),

   (a) \( p_T(x) > 25 \text{ GeV} \)

   (b) Rapidity, \( |\eta(x)| < 2.5 \)

   (c) Radial distance, \( \Delta R(x, y)_{x\neq y} \geq 0.4 \)

2. **Discovery cuts**

   (a) All the *Basic* cuts

   (b) \( p_T(e^+/e^-) > 150 \text{ GeV}; p_T(j_1) > 100 \text{ GeV} \)

   (c) \( M(e^+, e^-) > 150 \text{ GeV} \)

   (d) For at least one combination of \( (e, j_i) \): \( |M(e, j_i) - M_{e8}| \leq 0.2 M_{e8} \) where \( e = e^+ \) or \( e^- \) and \( j_i = j_1 \) or \( j_2 \).

   The invariant mass cut on \( M(e^+, e^-) \) can remove the \( Z \) inclusive background almost completely. We also demand that either of the electrons reconstruct to an \( e_8 \) when combined with any one of \( j_1 \) or \( j_2 \). We find that the “Discovery cuts” can reduce the SM background drastically. Especially for higher \( M_{e8} \) the background becomes much smaller compared to the signal, making it essentially background free. For example, taking \( M_{e8} = 0.5 \text{ TeV} \) (1 TeV) we estimate the total SM background with the “Discovery cuts” at the 14 TeV LHC to be about 4 fb (0.3 fb). Although these numbers are only rough
estimates for the actual SM backgrounds (as, e.g., we do not consider the effect of any loop induced diagrams) they indicate the SM backgrounds become very small compared to the signal (see Table 5.2) after the “Discovery cuts”. In Table 5.2 we show the signal with the above two cuts applied.

<table>
<thead>
<tr>
<th>$M_{\epsilon_8}$ (GeV)</th>
<th>$\Lambda = 5$ TeV</th>
<th>$\Lambda = 10$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic (fb)</td>
<td>Disco. (fb)</td>
</tr>
<tr>
<td>500</td>
<td>2.73E4</td>
<td>1.31E4</td>
</tr>
<tr>
<td>750</td>
<td>2.63E3</td>
<td>1.93E3</td>
</tr>
<tr>
<td>1000</td>
<td>442.95</td>
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</tr>
<tr>
<td>1250</td>
<td>105.21</td>
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<td>31.73</td>
<td>27.25</td>
</tr>
<tr>
<td>1750</td>
<td>11.53</td>
<td>9.76</td>
</tr>
<tr>
<td>2000</td>
<td>4.77</td>
<td>3.92</td>
</tr>
<tr>
<td>2250</td>
<td>2.26</td>
<td>1.80</td>
</tr>
<tr>
<td>2500</td>
<td>1.18</td>
<td>0.91</td>
</tr>
<tr>
<td>2750</td>
<td>0.65</td>
<td>0.49</td>
</tr>
<tr>
<td>3000</td>
<td>0.37</td>
<td>0.27</td>
</tr>
<tr>
<td>3250</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>3500</td>
<td>0.13</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 5.2: The combined signal after basic and “Discovery cuts” (see text for the definitions of the cuts) for $\Lambda = 5$ TeV and 10 TeV for different $M_{\epsilon_8}$ at the 14 TeV LHC.

### 5.4.4 LHC Reach with Combined Signal

We define the luminosity requirement for the discovery of $\epsilon_8$ as $L_D = \text{Max}(L_5, L_{10})$, where $L_5$ denotes the luminosity required to attain 5σ statistical significance for $S/\sqrt{B}$ and $L_{10}$ is the luminosity required to observe 10 signal events. We show $L_D$ as functions of $M_{\epsilon_8}$ for the “Discovery cuts” in Fig. 5.11 for $\Lambda = 5$ TeV and 10 TeV at the 14 TeV LHC. In Fig. 5.11 we also plot the $L_D$ using only the pair production process. To estimate the pair production from the combined signal we apply a set of kinematical cuts almost identical to the “Discovery cuts” except that now we demand that the two electrons and the two leading $p_T$ jets reconstruct to two $\epsilon_8$’s instead of one:

1. **Pair production extraction cuts**

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(a) All the *Basic* cuts

(b) $p_T(e^+/e^-) > 150\, \text{GeV}; p_T(j_1) > 100\, \text{GeV}$

(c) $M(e^+, e^-) > 150\, \text{GeV}$

(d) $|M(e^+, j_k) - M_{e_8}| \leq 0.2M_{e_8}$ and $|M(e^-, j_l) - M_{e_8}| \leq 0.2M_{e_8}$ with $k \neq l = \{1, 2\}$.

Figure 5.11: The required luminosity for discovery ($L_D$) as a function of $M_{e_8}$ with $\Lambda = 5$ TeV and 10 TeV at the 14 TeV LHC for combined production with “Discovery cuts” (see text for the definitions of the cuts). The $L_D$ for pair production is computed after demanding two $e_8$’s are reconstructed instead of one.

In Fig. 5.11, $L_D$ goes as $L_{10}$ for both pair and combined productions, as in these cases the backgrounds become quite small compared to the signals. With the “Discovery cuts” the reach goes up to 3.4 TeV and 2.9 TeV (4 TeV and 3.3 TeV) with 100 fb$^{-1}$ (300 fb$^{-1}$) integrated luminosity for $\Lambda = 5$ TeV and 10 TeV respectively at the 14 TeV LHC. This also shows that for $\Lambda = 5$ TeV (10 TeV) with combined signal at 14 TeV LHC with 300 fb$^{-1}$ integrated luminosity the reach goes up from the pair production by almost 1.2 TeV (0.5 TeV). However, we should keep in mind that this increase depends on $\Lambda$. As the single production c.s. goes like $1/\Lambda^2$, if $\Lambda$ is smaller than 5 TeV then the reach of the combined production will increase even more but for higher $\Lambda$ (like $\Lambda = 10$ TeV as shown in Fig. 5.11) its $L_D$ plot will approach more towards the pair production plot.