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# Leptonic signatures of doubly charged Higgs boson production at the LHC

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**ABSTRACT:** The production of doubly charged Higgs bosons ( $H^{\pm\pm}$ ) at the CERN LHC can give rise to distinctive multi-lepton signatures. The discovery potential of  $H^{\pm\pm}$  can be optimized by considering a search strategy which is sensitive to both of the dominant production mechanisms,  $q\bar{q} \rightarrow H^{++}H^{--}$  and  $q\bar{q}' \rightarrow H^{\pm\pm}H^{\mp}$ . We compare the discovery potential for the signatures of exactly four leptons and at least three leptons in the final state, using the same set of cuts. We have carried out fast detector simulations at the LHC for both signal and backgrounds for a wide range of values of the charged Higgs mass. We find that the use of the latter channel can substantially improve the detection prospects of the doubly charged Higgs boson at the LHC.

**KEYWORDS:** Higgs Physics, Beyond Standard Model

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**1 Introduction**

The firm evidence that neutrinos oscillate and possess small masses below the eV scale [1] necessitates physics beyond the Standard Model (SM), which could manifest itself at the CERN Large Hadron Collider (LHC) and/or in low energy experiments which search for lepton flavour violation (LFV) [2, 3]. Consequently, models of neutrino mass generation which can be probed at present and forthcoming experiments are of great phenomenological interest.

Neutrinos may obtain masses via the vacuum expectation value (vev) of a neutral Higgs boson in an isospin triplet representation [4–6, 8, 9]. A particularly simple implementation of this mechanism of neutrino mass generation is the “Higgs Triplet Model” (HTM) in which the SM Lagrangian is augmented solely by an SU(2) triplet of scalar particles with hypercharge  $Y = 2$  [4, 8, 9]. In the HTM, neutrinos acquire Majorana masses given by the product of a triplet Yukawa coupling ( $h_{ij}$ ) and a triplet vev ( $v_\Delta$ ). Consequently, there is a direct connection between  $h_{ij}$  and the neutrino mass matrix, which gives rise to phenomenological predictions for processes which depend on  $h_{ij}$  [10–23]. A distinctive signal of the HTM would be the observation of a doubly charged Higgs boson ( $H^{\pm\pm}$ ), whose mass ( $M_{H^{\pm\pm}}$ ) may be of the order of the electroweak scale. Such particles can be produced with sizeable rates at hadron colliders in the processes  $q\bar{q} \rightarrow H^{++}H^{--}$  [24–30] and  $q\bar{q}' \rightarrow H^{\pm\pm}H^\mp$  [24, 31, 32], where  $H^\pm$  is a singly charged Higgs boson in the same triplet representation. Direct searches for  $H^{\pm\pm}$  have been carried out at the Fermilab Tevatron, assuming the production channel  $q\bar{q} \rightarrow H^{++}H^{--}$  and the leptonic decays  $H^{\pm\pm} \rightarrow \ell_i^\pm \ell_j^\pm$  ( $\ell = e, \mu, \tau$ ), and mass limits in the range  $M_{H^{\pm\pm}} > 110 - 150$  GeV have been obtained [33–36]. The CERN Large Hadron Collider (LHC), using the above production mechanisms, will offer improved sensitivity to  $M_{H^{\pm\pm}}$  [18, 19, 28, 37–39].

The decay channels  $H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$  and  $H^\pm \rightarrow \ell^\pm \nu$  are the dominant ones if  $v_\Delta \lesssim 10^{-4} \text{ GeV}$ , and give rise to multi-lepton signatures. In the HTM, one expects  $v_\Delta \lesssim 10^{-4} \text{ GeV}$  if the triplet Yukawa coupling is larger than the smallest Yukawa coupling in the SM (i.e., the electron Yukawa coupling). One can define various multi-lepton signatures which originate from the production mechanisms  $q\bar{q} \rightarrow H^{++}H^{--}$  and  $q\bar{q}' \rightarrow H^{\pm\pm}H^\mp$ . The four-lepton signature ( $4\ell$ ) only receives a contribution from  $q\bar{q} \rightarrow H^{++}H^{--}$ , and the detection prospects in this channel at the LHC have been studied in [19, 28, 37–39]. Although this  $4\ell$  signature provides a very promising way to search for  $H^{\pm\pm}$ , it is not necessarily the channel which offers the best sensitivity for a given integrated luminosity and mass  $M_{H^{\pm\pm}}$ . Recently, attention has been given to the three-lepton channel [18, 19], which also has relatively small SM backgrounds. Importantly, the signature of three-leptons is sensitive to the production mechanism  $q\bar{q}' \rightarrow H^{\pm\pm}H^\mp$  [32]. The magnitudes of the cross sections of  $q\bar{q} \rightarrow H^{++}H^{--}$  and  $q\bar{q}' \rightarrow H^{\pm\pm}H^\mp$  are comparable in a large parameter space of the HTM, because the scalar potential of the model gives  $M_{H^{\pm\pm}} \sim M_{H^\pm}$  (unless a specific scalar quartic coupling is taken to be *fairly* large). In order to improve the sensitivity of the LHC to  $M_{H^{\pm\pm}}$ , one can define two distinct signatures consisting of three leptons, in which two of the leptons have the same electric charge and are assumed to originate from  $H^{\pm\pm}$  (which is produced in both production mechanisms,  $q\bar{q} \rightarrow H^{++}H^{--}$  and  $q\bar{q}' \rightarrow H^{\pm\pm}H^\mp$ ): i) the signature of “exactly three leptons” ( $3\ell$ ), [19], and ii) the signature of “three or more leptons” ( $\geq 3\ell$ ) [35]. Different sensitivity to  $M_{H^{\pm\pm}}$  is expected in these two channels.

Detection prospects at the LHC are best for  $\ell = e, \mu$ , for which there are several exclusive three-lepton channels, e.g.  $eee, \mu\mu\mu, e\mu\mu$  etc [22]. However, in the region of high invariant mass for a pair of same-sign leptons (e.g.,  $m_{\ell\ell} > 200 \text{ GeV}$ ) one expects similar detection efficiencies and SM backgrounds in these exclusive three-lepton channels with  $\ell = e, \mu$ . Therefore, to optimise the sensitivity to  $M_{H^{\pm\pm}}$  it is reasonable to define an inclusive signature in which  $e^\pm$  and  $\mu^\pm$  are treated as identical particles, and this is the approach which is taken in [19]. The signature of  $3\ell$  (with  $\ell = e, \mu$ ) is studied in [19] and it is shown that the sensitivity to  $M_{H^{\pm\pm}}$  is significantly superior to that of the  $4\ell$  channel. This very promising result can be further improved, because the  $\geq 3\ell$  channel is expected to give even greater sensitivity to  $M_{H^{\pm\pm}}$  than the  $3\ell$  channel. In this work we study the signature of  $\geq 3\ell$  and compare its sensitivity to  $M_{H^{\pm\pm}}$  with that obtained for the  $4\ell$  channel. Our study is the first simulation of the signature  $\geq 3\ell$  at LHC that includes both production mechanisms  $q\bar{q} \rightarrow H^{++}H^{--}$  and  $q\bar{q}' \rightarrow H^{\pm\pm}H^\mp$ . We show that the  $\geq 3\ell$  channel is the optimum search strategy for  $H^{\pm\pm}$ . We note that the most recent search by the D0 collaboration [35] uses the strategy of  $> 3\ell$  in the context of a search for three muons ( $\mu^\pm \mu^\pm \mu^\mp$ ), with the assumption that production of  $H^{\pm\pm}$  is only by  $q\bar{q} \rightarrow H^{++}H^{--}$ .

The paper is organized as follows. In section 2 we will briefly review the HTM model. In section 3 we discuss the production of doubly charged Higgs bosons at hadronic colliders. In the same section we will describe our analysis setup and framework for simulations of backgrounds and signal processes. The results of our simulations are given in section 4. Finally we will conclude with a summary of our results in section 5

## 2 The Higgs triplet model

The HTM model [4, 8, 9] is an extension of the SM in which only the scalar sector is augmented with a Higgs triplet. It is a particularly simple model which contains a doubly charged scalar. The model has the following  $SU(2) \otimes U(1)_Y$  gauge-invariant Yukawa interactions:

$$\mathcal{L} \ni h_{ij} \psi_{iL}^T C i \sigma_2 \Delta \psi_{jL} + \text{h.c.}, \quad (2.1)$$

where the triplet Yukawa couplings  $h_{ij}(i, j = e, \mu, \tau)$  are complex and symmetric,  $C$  is the Dirac charge conjugation operator,  $\sigma_2$  is a Pauli matrix,  $\psi_{iL} = (\nu_i, l_i)_L^T$  is a left-handed lepton doublet, and  $\Delta$  is a  $2 \times 2$  representation of the  $Y = 2$  complex triplet fields ( $\delta^{++}, \delta^+, \delta^0$ ):

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}. \quad (2.2)$$

Note that the mass eigenstate  $H^{\pm\pm}$  is entirely composed of the triplet field ( $H^{\pm\pm} \equiv \delta^{\pm\pm}$ ), while  $H^\pm$  is predominantly  $\delta^\pm$ , with a small component of isospin doublet scalar ( $\Phi$ ). A non-zero Higgs triplet VEV,  $\langle \delta^0 \rangle = v_\Delta/\sqrt{2}$ , gives rise to the following Majorana mass matrix for neutrinos:

$$m_{ij} = 2h_{ij} \langle \delta^0 \rangle = \sqrt{2} h_{ij} v_\Delta. \quad (2.3)$$

Realistic neutrino masses can be obtained with a perturbative  $h_{ij}$  provided that  $v_\Delta \gtrsim 1 \text{ eV}$ . The presence of a non-zero  $v_\Delta$  gives rise to  $\rho \neq 1$  at tree level, where  $\rho \equiv M_W^2/(M_Z^2 \cos^2 \theta_W)$ . Therefore  $v_\Delta \lesssim 1 \text{ GeV}$  is necessary in order to comply with the measurement of  $\rho \sim 1$ . This simple expression of tree-level masses for the observed neutrinos is essentially the main motivation for studying the HTM. It provides a direct connection between  $h_{ij}$  and the neutrino mass matrix, which gives rise to phenomenological predictions for processes which depend on  $h_{ij}$  [10, 13–23].

The mass matrix  $m_{ij}$  for three Dirac neutrinos is diagonalized by the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix  $V_{\text{PMNS}}$  [40, 41]. For Majorana neutrinos (which is the case in HTM), two additional phases appear, and then the mixing matrix  $V$  becomes

$$V = V_{\text{PMNS}} \times \text{diag}(1, e^{i\phi_1/2}, e^{i\phi_2/2}), \quad (2.4)$$

where  $\phi_1$  and  $\phi_2$  are referred to as the Majorana phases [8, 42, 43] and  $-\pi \leq \phi_1, \phi_2 < \pi$ . One has the freedom to work in the basis in which the charged lepton mass matrix is diagonal, and then the neutrino mass matrix is diagonalized by  $V_{\text{PMNS}}$ . Using eq. (2.3) one can write the couplings  $h_{ij}$  as follows [10–13]:

$$h_{ij} = \frac{m_{ij}}{\sqrt{2}v_\Delta} \equiv \frac{1}{\sqrt{2}v_\Delta} \left[ V_{\text{PMNS}} \text{diag}(m_1, m_2 e^{i\phi_1}, m_3 e^{i\phi_2}) V_{\text{PMNS}}^T \right]_{ij}. \quad (2.5)$$

Here  $m_1, m_2$  and  $m_3$  are the absolute masses of the three neutrinos. Neutrino oscillation experiments are sensitive to mass-squared differences,  $\Delta m_{21}^2 (\equiv m_2^2 - m_1^2)$  and  $\Delta m_{31}^2 (\equiv m_3^2 - m_1^2)$ . Since the sign of  $\Delta m_{31}^2$  is undetermined at present, distinct patterns for the

neutrino mass hierarchy are possible. The case with  $\Delta m_{31}^2 > 0$  is referred to as *normal hierarchy* (NH) where  $m_1 < m_2 < m_3$ , and the case with  $\Delta m_{31}^2 < 0$  is known as *inverted hierarchy* (IH) where  $m_3 < m_1 < m_2$ . However, information on the mass  $m_0$  of the lightest neutrino (either  $m_1$  or  $m_3$ ) and the Majorana phases cannot be obtained from neutrino oscillation experiments. This is because the oscillation probabilities are independent of these parameters, not only in vacuum but also in matter. An attractive feature of the HTM is this simple relationship between the triplet Yukawa couplings and the parameters of the neutrino mass matrix (many of which are measurable) given in eq. (2.5). In contrast, eq. (2.5) does not hold in other models with a doubly charged scalar (e.g., the Left-Right symmetric model in which the couplings  $h_{ij}$  are essentially arbitrary.)

In this work we are concerned with the case of the leptonic decays of  $H^{\pm\pm}$  dominating, which is realized if  $h_{ij}$  are larger than the smallest Yukawa coupling in the SM (*i.e.*, the electron Yukawa coupling,  $h_e \sim 10^{-6}$ ). From eq. (2.5) it follows that  $v_\Delta \lesssim 0.1$  MeV in this scenario, and thus the decay  $H^{\pm\pm} \rightarrow W^\pm W^\pm$  (which depends on  $v_\Delta$ ) is negligible. Moreover, in the HTM the lifetime of  $H^{\pm\pm}$  is always short enough to ensure that it decays in the detectors of the Tevatron and the LHC [28]. For very small values of  $v_\Delta$  (*e.g.*,  $v_\Delta < 10$  eV), the magnitude of the Yukawa couplings  $h_{ij}$  approaches unity. In this case, the charged scalars (which we assume to have a mass of the order of the electroweak scale) would induce potentially observable BR's for LFV decays such as  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow eee$  and  $\tau \rightarrow lll$  (*e.g.*, see [44]), whose decay rates depend on the parameters of the neutrino mass matrix, the absolute values of  $h_{ij}$ , and  $M_{H^{\pm\pm}}$  or  $M_{H^\pm}$  [13, 14, 21]. Such constraints can be satisfied for appropriately small  $h_{ij}$ , the most severe constraint being from  $\mu \rightarrow eee$  (which gives  $h_{ee}h_{e\mu} \lesssim 10^{-7}$ ). In the parameter space  $10^{-6} \lesssim h_{ij} \lesssim 10^{-3}$ , the constraints from the above LFV decays are satisfied, even for values of  $M_{H^{\pm\pm}}$  of the order of the electroweak scale. The BR of  $H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$  depends on the six parameters of the neutrino mixing matrix,  $V$ , (with the dominant uncertainty arising from the unknown Majorana phases,  $\phi_1$  and  $\phi_2$ ), the unknown mass of the lightest neutrino ( $m_0$ ), the mass splittings of the neutrinos, and the ignorance of the neutrino mass hierarchy (normal or inverted) [13].

Detailed studies of  $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm)$  have been performed in [15–18]. Notably,  $\text{BR}(H^\pm \rightarrow \ell^\pm \nu)$  (in which the three flavours of neutrinos are summed over) does not depend on the Majorana phases, and the dominant uncertainty is from  $m_0$  and the neutrino mass hierarchy [18]. Importantly,  $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \sim 100\%$  and  $\text{BR}(H^\pm \rightarrow \ell^\pm \nu) \sim 100\%$  for a given lepton flavour are not possible in the HTM. Moreover,  $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \sim 100\%$  and  $\text{BR}(H^\pm \rightarrow \ell^\pm \nu) \sim 100\%$  are not possible even when summing over  $\ell = e, \mu$ , although values as high as  $\sim 70\%$  are possible in specific regions of the parameter space of the neutrino mass matrix. A generic model containing  $H^{\pm\pm}$  can have  $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) \sim 100\%$  (summing over  $\ell = e, \mu$ ) for appropriately chosen  $h_{ij}$ , *e.g.*, the LR symmetric model with  $h_{ee}, h_{e\mu}, h_{\mu\mu} \gg h_{e\tau}, h_{\mu\tau}, h_{\tau\tau}$ . In direct searches for  $H^{\pm\pm}$  the derived lower limits on  $M_{H^{\pm\pm}}$  are usually given for the extreme case of  $\text{BR}=100\%$ , and this will be discussed in more detail in the next section.

### 3 Searches for doubly charged Higgs bosons at hadron colliders

Direct searches for  $H^{\pm\pm}$  have been carried out at the Fermilab Tevatron [33–36], assuming the production mechanism at partonic level given by  $q\bar{q} \rightarrow \gamma^*, Z^* \rightarrow H^{++}H^{--}$ , whose cross section depends on only one unknown parameter,  $M_{H^{\pm\pm}}$ . Production mechanisms which depend on the triplet VEV ( $q\bar{q}' \rightarrow W^{\pm*} \rightarrow W^\mp H^{\pm\pm}$  and fusion via  $W^{\pm*}W^{\pm*} \rightarrow H^{\pm\pm}$  [29, 30, 46]) are not competitive with  $q\bar{q} \rightarrow H^{++}H^{--}$  at the energies of the Tevatron. All searches assume the leptonic decay mode  $H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$ , for which there are six possibilities ( $ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau$ ).

The CDF collaboration searched for three final states,  $H^{\pm\pm} \rightarrow e^\pm e^\pm, e^\pm\mu^\pm, \mu^\pm\mu^\pm$ , requiring at least one pair of same-sign leptons with high invariant mass [33]. The integrated luminosity used was  $0.24 \text{ fb}^{-1}$  and the mass limits  $M_{H^{\pm\pm}} > 133, 113, 136 \text{ GeV}$  were obtained for the decay channels  $H^{\pm\pm} \rightarrow e^\pm e^\pm, e^\pm\mu^\pm, \mu^\pm\mu^\pm$ , respectively, assuming BR=100% in a given channel. The D0 collaboration [34, 35] searched for  $H^{\pm\pm} \rightarrow \mu^\pm\mu^\pm$ , and derived the mass limit  $M_{H^{\pm\pm}} > 150 \text{ GeV}$  [35] using  $1.1 \text{ fb}^{-1}$  of integrated luminosity. The main difference between these searches by D0 is the requirement in the most recent search [35] of a third  $\mu$  of opposite sign to the two same-sign  $\mu$ , where the latter is assumed to originate from the decay of one of the pair-produced  $H^{\pm\pm}$ . This extra requirement suppresses backgrounds from  $\gamma/Z \rightarrow \mu^+\mu^-$  and multijets, which were less than one event for the integrated luminosity of  $0.11 \text{ fb}^{-1}$  used in [34], but became non-negligible for the search in [35] with  $1.1 \text{ fb}^{-1}$ . The requirement of a third lepton is necessary for the future Tevatron searches in order to reduce the SM backgrounds. At the Tevatron, the main backgrounds to the three-lepton signal with  $\ell = e, \mu$  are from  $WZ$  and  $ZZ$  production. Two decay channels involving  $\tau$  ( $H^{\pm\pm} \rightarrow e^\pm\tau^\pm, \mu^\pm\tau^\pm$ ), were searched for by the CDF collaboration in [36], and there has been no search for  $H^{\pm\pm} \rightarrow \tau^\pm\tau^\pm$ .

As discussed in section 2, in the HTM one has  $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm) < 100\%$  in a given channel, and thus the above mass limits for  $M_{H^{\pm\pm}}$  (which assume BR=100%) are weakened when applied to the HTM. The expected number of  $H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$  events scales linearly in BR (for searches for a single pair of same-sign leptons [33, 34]) or quadratically in BR (for searches which require a third lepton or more [35]), and so the mass limits are weakened accordingly.

All the above searches at the Tevatron assume *only* the production mechanism  $q\bar{q} \rightarrow \gamma^*, Z^* \rightarrow H^{++}H^{--}$ . However, the partonic process  $q\bar{q}' \rightarrow W^* \rightarrow H^{\pm\pm}H^\mp$  [24, 31, 32] has a cross section at hadron colliders comparable to that of  $q\bar{q} \rightarrow H^{++}H^{--}$  for  $M_{H^\pm} \sim M_{H^{\pm\pm}}$ , and thus the former will also contribute to the search for  $H^{\pm\pm}$ . In ref. [32], it is suggested that the search potential at hadron colliders can be improved by considering the following inclusive single  $H^{\pm\pm}$  cross section ( $\sigma_{H^{\pm\pm}}$ ):

$$\sigma_{H^{\pm\pm}} = \sigma(p\bar{p}, pp \rightarrow H^{++}H^{--}) + \sigma(p\bar{p}, pp \rightarrow H^{++}H^-) + \sigma(p\bar{p}, pp \rightarrow H^{--}H^+) \quad (3.1)$$

At the Tevatron  $\sigma(p\bar{p} \rightarrow H^{++}H^-) = \sigma(p\bar{p} \rightarrow H^{--}H^+)$  while at the LHC  $\sigma(pp \rightarrow H^{++}H^-) > \sigma(pp \rightarrow H^{--}H^+)$ . These two production mechanisms have different QCD  $K$  factors. Explicit calculations [27] for  $p\bar{p}, pp \rightarrow H^{++}H^{--}$  give around  $K = 1.3$  at the Tevatron and  $K = 1.25$  at the LHC, with a dependence on  $M_{H^{\pm\pm}}$ . In reality, the  $K$

factor for  $p\bar{p}, pp \rightarrow H^{\pm\pm}H^\mp$  is expected to be very similar (but not identical) to that for  $p\bar{p}, pp \rightarrow H^{++}H^{--}$ , with some dependence on the mass splitting  $M_{H^{\pm\pm}} - M_{H^\pm}$ . In [18, 32] the  $K$  factors are taken to be equal. We note that  $p\bar{p}, pp \rightarrow H^{++}H^{--}$  also receives a contribution from real photon annihilation [28], which causes an increase in the cross section of around 10% at the LHC, but much less at the Tevatron. In our simulation analysis however we do not include this correction.

#### 4 Simulations of signal and backgrounds at the LHC

Several studies have been performed to study the doubly charged Higgs in the decay channel  $H^{\pm\pm} \rightarrow \ell_i^\pm \ell_j^\pm$  ( $i, j = e, \mu, \tau$ ) at the LHC. The production mechanism  $q\bar{q} \rightarrow \gamma^*, Z^* \rightarrow H^{++}H^{--}$  followed by decay  $H^{++}H^{--} \rightarrow \ell^+\ell^+\ell^-\ell^-$  is studied in [18, 19, 28, 37–39]. Only two among these studies also take into account the production mechanism  $pp \rightarrow W^{\pm*} \rightarrow H^{\pm\pm}H^\mp$  [18, 19], followed by the decays  $H^{\pm\pm} \rightarrow \ell_i^\pm \ell_j^\pm$  ( $i, j = e, \mu, \tau$ ) and  $H^\pm \rightarrow \ell_i^\pm \nu$ . The LHC sensitivity to  $H^{\pm\pm} \rightarrow \ell_i^\pm \ell_j^\pm$  considerably extends that at the Tevatron, due to the increased cross sections and larger luminosities. The analysis of ref. [38] shows that  $H^{\pm\pm}$  can be discovered for  $m_{H^{\pm\pm}} < 800$  GeV and  $\mathcal{L} = 50 \text{ fb}^{-1}$ , assuming  $\text{BR}(H^{\pm\pm} \rightarrow \mu^\pm \mu^\pm) = 100\%$ . Importantly, all the above simulations suggest that as little as  $\mathcal{L} = 1 \text{ fb}^{-1}$  is needed for the discovery of  $m_{H^{\pm\pm}} < 400$  GeV if one of  $\text{BR}(H^{\pm\pm} \rightarrow e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm)$  is large, and hence such a light  $H^{\pm\pm}$  would be found very quickly at the LHC. The signal from  $q\bar{q} \rightarrow \gamma^*, Z^* \rightarrow H^{++}H^{--}$  and decay  $H^{++}H^{--} \rightarrow \ell^+\ell^+\ell^-\ell^-$  is usually taken to be four leptons, which are isolated and have sufficiently large transverse energy. In ref. [38] the signal is taken to be  $4\mu$ . In ref. [37], where little Higgs models are considered, the signal is defined as  $4\ell$  where  $\ell = \mu, \tau$  (and  $e$  is not included), and five different four-lepton signatures are studied (one of which being  $4\mu$ ). In ref. [28]  $e$  and  $\mu$  are treated as the same particle, and a parton-level study of the four-lepton signature is performed. In ref. [39] two signatures are defined: i) four leptons and ii) at least three leptons. It is shown that superior sensitivity to  $M_{H^{\pm\pm}}$  is obtained for the signature of at least three leptons.

As discussed earlier, the production mechanism  $pp \rightarrow W^{\pm*} \rightarrow H^{\pm\pm}H^\mp$  will contribute to the signal for  $H^{\pm\pm}$  if three (or more) leptons are required. The simulation in ref. [19] is the first study of the mechanism  $pp \rightarrow H^{\pm\pm}H^\mp$  together with  $pp \rightarrow H^{++}H^{--}$ , with the aim of improving the sensitivity to  $M_{H^{\pm\pm}}$  at the LHC. In ref. [19]  $e$  and  $\mu$  are not distinguished, and such an inclusive channel has the advantage of maximizing the sensitivity to  $M_{H^{\pm\pm}}$  for a given integrated luminosity, and for the general case of  $\text{BR} < 100\%$  for a given flavour of lepton. Both a four-lepton signature and a three-lepton signature are studied, and the sensitivity to  $M_{H^{\pm\pm}}$  for the two signatures is compared, assuming  $M_{H^{\pm\pm}} = M_{H^\pm}$ . The three-lepton signature is defined as being *exactly* three leptons ( $3\ell$ ), i.e., a fourth lepton is vetoed. Note that this three-lepton signature differs from that defined in the latest search for  $H^{\pm\pm}$  at the Tevatron [35] in which a fourth lepton is not vetoed ( $\geq 3\ell$ ).

In ref. [19] it is concluded that the three-lepton signature offers considerably greater discovery potential for  $H^{\pm\pm}$  in the HTM than the signature of four leptons (note that the same conclusion is obtained in [39], even without including  $pp \rightarrow H^{\pm\pm}H^\mp$ ). The main reason for the superior sensitivity of the three-lepton signature in [19] is the extra

contribution from  $pp \rightarrow H^{\pm\pm}H^\mp$  (which does not contribute to the four-lepton signature). Although the SM background for the three-lepton signature is larger than that for the four-lepton signature, in the region of high invariant mass of  $\ell^\pm\ell^\pm$  (relevant for  $M_{H^{\pm\pm}} > 200$  GeV) the backgrounds are still sufficiently small, which gives rise to superior sensitivity to  $M_{H^{\pm\pm}}$  for the three-lepton signature. Moreover, ref. [19] used different sets of cuts for the three-lepton and four-lepton signatures.

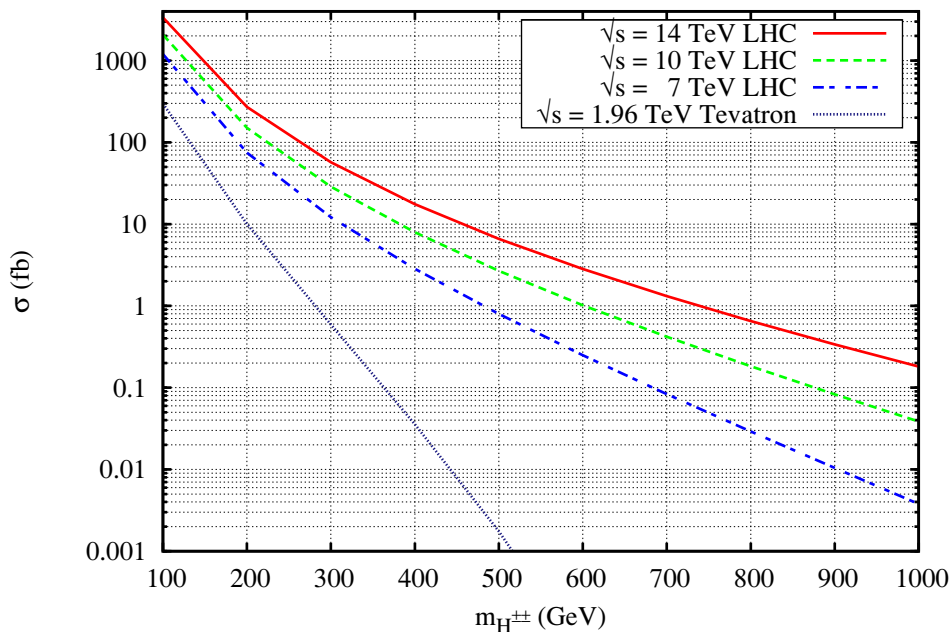
In ref. [18], a parton-level study at the LHC was performed for the detection prospects of the production channel  $pp \rightarrow H^{\pm\pm}H^\mp$  alone, followed by the decays  $H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$  and  $H^\pm \rightarrow \ell^\pm\nu$ , where both  $e$  and  $\mu$  contributions are summed together in an inclusive approach like that in ref. [19]. The strategy in [18] is to isolate the contribution from  $pp \rightarrow H^{\pm\pm}H^\mp$  and remove that from  $pp \rightarrow H^{++}H^{--}$ , with the aim of probing the vertex  $H^{\pm\pm}H^\mp W^\pm$ , which is present in the HTM but not in models with SU(2) singlet scalars. A cut is imposed on missing energy (which originates from  $H^\pm \rightarrow \ell^\pm\nu$ ) in order to remove the contribution from  $pp \rightarrow H^{++}H^{--}$ . Therefore the approach of ref. [18] contrasts with that of [19] (and our approach), where in the latter the cuts are designed to keep signal events from both  $pp \rightarrow H^{++}H^{--}$  and  $pp \rightarrow H^{\pm\pm}H^\mp$  in order to optimize sensitivity to  $M_{H^{\pm\pm}}$  for a given integrated luminosity.

The main features of our analysis are:

- In order to analyze the signature of  $\geq 3\ell$  as mentioned above we have to consider the  $H^{\pm\pm}H^\mp W^\pm$  vertex. This vertex was not available in PYTHIA [48] for the HTM model. For our analysis we have used CalcHEP [47] and incorporated this vertex in the model file.
- We have included K-factors for both signal and background events.
- We have performed a detailed realistic detector simulation using the fast detector simulator ATLFast for both signal and background processes.
- We have considered the  $\geq 3\ell$  signature and compared its discovery potential with that for the  $4\ell$  signature at the LHC.

Hereafter, we will refer to electrons and/or muons collectively as “leptons” ( $\ell = e, \mu$ ). We will further assume the idealized case of  $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm) = 100\%$  and  $\text{BR}(H^\pm \rightarrow \ell^\pm\nu_\ell) = 100\%$ , i.e., the decays of the charged Higgs bosons are saturated by the electronic and muonic modes. We do this in order to provide a simple comparison of the discovery potential of the two signatures under investigation. Moreover, such extreme branching ratios are generally used when deriving limits on  $M_{H^{\pm\pm}}$  from direct searches. In contrast, we note that representative branching ratios in the HTM were used in [19], for which decay modes of  $H^{\pm\pm}$  involving  $\tau$  were sizeable. Careful attention was given to secondary electrons and muons which originate from decays like  $H^{\pm\pm} \rightarrow \mu^\pm\tau^\pm$  followed by  $\tau \rightarrow \ell\nu$ , and their effect on the dilepton invariant mass distribution was studied. In our analysis the decay modes of  $H^{\pm\pm}$  involving  $\tau$  are absent, and so there are no such secondary leptons. For the cases of  $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm) < 100\%$  and  $\text{BR}(H^\pm \rightarrow \ell^\pm\nu_\ell) < 100\%$  (as discussed in section 2 for the HTM) our results will need to be scaled by multiplicative factors of branching ratios.





**Figure 1.** Cross section of inclusive doubly charged Higgs bosons production (eq. 3.1) as a function of  $M_{H^{++}}$ . The K-factor of the processes is taken to be 1.25 for LHC and 1.3 for Tevatron.

Moreover, for non-zero BRs of  $H^{\pm\pm}$  and  $H^\pm$  into final states which contain  $\tau$  leptons, the influence of the secondary leptons (which originate from the decay of the  $\tau$  leptons) on the signal will need to be included. For definiteness, we take  $M_{H^{++}} = M_{H^\pm}$  as the mass difference is fairly small for most of the parameter space in the HTM.

The cross section for the inclusive production of doubly charged Higgs bosons at hadronic colliders is plotted in figure 1 as a function of the doubly charged Higgs mass. In this plot we show the production cross sections as given in eq. (3.1) for the LHC at the center-of-mass (CM) energy of  $\sqrt{s} = 7, 10, 14$  TeV and for the Tevatron  $\sqrt{s} = 1.96$  TeV. The LHC is expected to take around  $1 \text{ fb}^{-1}$  of integrated luminosity at  $\sqrt{s} = 7$  TeV in its first two years of operation. Subsequently, the machine is planned to run at the design energy of  $\sqrt{s} = 14$  TeV. For completeness, we also show the cross section at an intermediate energy of  $\sqrt{s} = 10$  TeV because operation at this energy has been discussed. In our later simulations, we have assumed the CM energy of  $\sqrt{s} = 14$  TeV at the LHC. We have used the leading-order (LO) CTEQ6L parton distribution functions (PDF) with two-loop  $\alpha_s$  running, and identified both the factorization scale  $\mu_f$  and the renormalization scale  $\mu_r$  with the partonic CM energy  $\hat{s}$ .

#### 4.1 Framework for event generation

The SM background processes we have considered for both the  $\geq 3\ell$  and  $4\ell$  channels are:

- $ZZ$  with each of the  $Z$ 's decaying leptonically.
- $W^\pm Z$  with each of the weak gauge bosons decaying leptonically.

$m_{H^{\pm\pm}}$ (GeV)	200	300	400	500	600	700	800
Events generated	300 K	150 K	100 K	100 K	80 K	80 K	60 K

**Table 1.** Number of signal events generated where K stands for  $10^3$ . These events are then scaled to the luminosity of  $\mathcal{L} = 10 \text{ fb}^{-1}$ .

Process	ZZ	WZ	WWW	$t\bar{t}$	Z bb	W bb	Ztt	Wtt
Decay modes	all	all	all	SL	SL	SL	SL	SL
Events	1.5 M	1.5 M	300 K	90 M	1.2 M	900 K	150 K	800 K

**Table 2.** Number of background events generated where K stands for  $10^3$  and M stands for  $10^6$ . The second row corresponds to the decay modes considered, and SL indicates “semi-leptonic.” These events are then scaled to the luminosity of  $\mathcal{L} = 10 \text{ fb}^{-1}$ .

- $t\bar{t}$  with  $t \rightarrow Wb$ , and  $W$ 's and  $b$  decaying (semi)leptonically.
- $Zbb$  with  $Z$  and  $b$  decaying (semi)leptonically.
- $Wbb$  with  $W$  and  $b$  decaying (semi)leptonically.
- $Ztt$  with  $Z$  and  $t$  decaying (semi)leptonically.
- $Wtt$  with  $W$  and  $t$  decaying (semi)leptonically.
- $W^{\pm}W^{\mp}W^{\pm}$  with each of the  $W$ 's decaying leptonically.

The setup for signal and background event generations is the following:

- *Signal event generation:* we have used CalcHEP v.2.5.4 [47] for calculating cross sections. For this purpose we have implemented the relevant interaction vertices in the CalcHEP model files. The partonic level signal events have been generated using CalcHEP and then passed to PYTHIA v.6.4.21 [48] via Les Houches Event (LHE) interface [49–51] in order to include initial state radiation/final state radiation (ISR/FSR) effects. The number of signal events generated are given in table 1. These events were then scaled to the luminosity of  $\mathcal{L} = 10 \text{ fb}^{-1}$ .
- *Background event generation:* we have generated the  $t\bar{t}$ ,  $ZZ$ ,  $W^{\pm}Z$  events directly using PYTHIA, and the  $Zbb$ ,  $W^{\pm}bb$ ,  $Ztt$ ,  $W^{\pm}tt$  events first using CalcHEP and then interfaced with PYTHIA for ISR/FSR. The number of background events generated are given in table 2. These events were scaled to the luminosity of  $\mathcal{L} = 10 \text{ fb}^{-1}$ .

In order to make more realistic estimates of the signal and background events, we have further processed both of them through the fast ATLAS detector simulator ATLFAST [53]. The resulting events have been analyzed within the ROOT framework. The detector simulator ATLFAST provides simple detector simulation and jet reconstruction using a simple cone algorithm. It further identifies isolated leptons, photons,  $b$  and  $\tau$  jets, and also reconstructs missing energy. In our analysis for the LHC, we have assumed the CM energy

Process	$WZ$	$ZZ$	$t\bar{t}$	$Zbb$	$Ztt$	$Wbb$	$H^{\pm\pm}H^{\mp\mp}, H^{\pm\pm}H^{\mp}$
K-factors	1.5	1.35	1.67	2.4	1.35	2.57	1.25

**Table 3.** K-factors for the background and signal processes at LHC.

of 14 TeV and luminosity  $\mathcal{L} = 10 \text{ fb}^{-1}$ . The K-factors for signals and backgrounds that we have used are listed in table 3.

In order to improve the search potential for the doubly charged Higgs boson at the LHC, we want to advocate the D0 search strategy [35] of looking for  $\geq 3\ell$ . This is in contrast with the current LHC search strategy [37] of looking for exactly four leptons. Accordingly, we will present our simulation results for exactly four-lepton signature and  $\geq 3$  lepton signature.

## 4.2 Signature of four leptons

This is the signature ( $4\ell$ ,  $\ell = e, \mu$ ) when we have the pair production of doubly charged Higgs bosons via the process  $pp \rightarrow H^{\pm\pm}H^{\mp\mp}$  followed by leptonic decays  $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ . This signature has been simulated within the context of LHC in refs. [19, 37–39].

We use the following *pre-selection cuts* on signal and background events [19]:

- There are exactly four leptons with two for each charge sign ( $\ell^+\ell^+\ell^-\ell^-$ ) in each event.
- Each of the leptons has  $|p_T^\ell| > 5 \text{ GeV}$  and pseudorapidity in the range  $|\eta| < 2.5$ .
- Amongst the four leptons, at least two of the leptons have  $|p_T^\ell| > 30 \text{ GeV}$ . This cut reduces the backgrounds where the leptons originate from the semileptonic  $b$  decays as they tend to be less energetic.
- Opposite-sign dilepton invariant mass cut:  $m_{\ell^+\ell^-} > 20 \text{ GeV}$ . This is done in order to suppress the backgrounds where the opposite-sign lepton pair comes from a photon.

We impose additional cuts to further improve the signal significance:

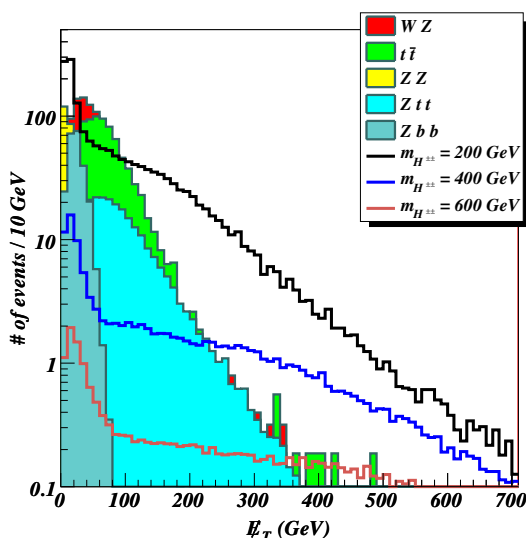
- (a) The  $Z$  window cut. The invariant mass of opposite-sign dileptons is required to be sufficiently far from the  $Z$  mass:  $|m_{\ell^+\ell^-} - M_Z| > 10 \text{ GeV}$ . This removes events where the leptons come from the  $Z$  decay.
- (b) The  $H_T$  cut. One can also use the total transverse energy ( $H_T$ ) as a parameter to distinguish signals from backgrounds. The total transverse energy is defined as

$$H_T = \sum_{\ell, E_T} |\vec{p}_T| . \tag{4.1}$$

The  $H_T$  distribution of signals tends to peak around the heavy particle mass, and hence this cut can be used to suppress the SM background processes that involve relatively light particles. We will show the results for  $H_T > 300$  and  $500 \text{ GeV}$ . We note that this  $H_T$  cut was also used in the study of the  $4\ell$  signature in ref. [37], but it was not used in the study of ref. [19].

Cut	Backgrounds						Signal ( $M_{H^{\pm\pm}}$ )	
	$WZ$	$ZZ$	$t\bar{t}$	$Zbb$	$Ztt$	$Wtt$	200 GeV	600 GeV
Pre-selection	0.2	130.5	1.3	0.2	122.6	0.1	400.1	4.2
$ m_{\ell^+\ell^-} - m_Z  > 10 \text{ GeV}$	0.1	2.1	0.3	0	2.1	0.1	330.6	4.1
$H_T > 300 \text{ GeV}$	0	0.4	0	0	1.2	0	327.9	4.1
$H_T > 500 \text{ GeV}$	0	0.1	0	0	0.3	0	222.9	4.1
$\mathcal{S}$							48.7	3.7

**Table 4.** Background and signal events surviving the cuts for exactly 4-lepton final states. For these numbers we have taken  $\mathcal{L} = 10 \text{ fb}^{-1}$  and  $\sqrt{s} = 14 \text{ TeV}$ .



**Figure 2.**  $E_T$  distribution for doubly charged Higgs production (signal) and SM backgrounds after imposition of the pre-selection cuts. We have taken the CM energy of  $\sqrt{s} = 14 \text{ TeV}$  and luminosity  $\mathcal{L} = 10 \text{ fb}^{-1}$ .

The effects of the cuts on signal and background events for two indicative masses of the doubly charged Higgs boson are given in table 4. After the pre-selection cuts, the dominant backgrounds are  $ZZ$  and  $Ztt$ , which are then significantly reduced by the  $Z$  window cut. For large  $M_{H^{\pm\pm}}$ , the  $Z$  window and  $H_T$  cuts only reduce the number of signal events by a negligible amount and hence the significance of the signal is improved.

### 4.3 Signature of at least three leptons

The study of the signature with exactly three leptons ( $3\ell$ ) was done in ref. [19], with the motivation of comparing the detection prospects of three distinct types of seesaw-based models of neutrino mass generation (one of which being the HTM). It was acknowledged that such a signature is not necessarily the one which optimizes the discovery potential in a given model. In this paper, we are concerned with optimizing the sensitivity to  $M_{H^{\pm\pm}}$  and thus we consider the signature of  $\geq 3\ell$  as done in the D0 search [35]. As emphasized earlier, both the pair production and single production of the doubly charged Higgs boson

Cuts ↓	Backgrounds							Signal ( $M_{H^{\pm\pm}}$ )	
	$WZ$	$WWW$	$ZZ$	$t\bar{t}$	$Zbb$	$Ztt$	$Wtt$	200	600
Pre-selection	591.7	3.5	203.6	159.9	57.7	212.5	9.7	1570.4	17.6
$ m_{\ell^+\ell^-} - m_Z  > 10$ GeV	50.9	2.7	12.1	113.2	0.9	33.4	7.4	1397.8	17.3
$H_T > 300$ GeV	7.5	1.1	1.6	8.9	0	17	3.4	1351.1	17.3
$H_T > 500$ GeV	1.7	0.3	0.4	0.9	0	3.2	0.6	796.2	17.3
$\mathcal{S}$								77.4	5

**Table 5.** Background and Signal events surviving the cuts for at least 3 leptons in the final state. We have taken  $\mathcal{L} = 10 \text{ fb}^{-1}$  and  $\sqrt{s} = 14 \text{ TeV}$ .

contribute to the signature and hence increase the signal events. For this analysis, we have used cuts similar to those in section 4.2. The only difference is that instead of singling out events with exactly four leptons, here we select events that have at least three leptons, of which two have the same sign. We would like to note that ref. [19] used a slightly different set of *pre-selection* cuts for studying the *exactly three-lepton* signature. For the *exactly three-lepton* signature, they chose events that had *at least two same-sign* leptons with  $p_T > 30$  GeV. Also, the *pre-selection* cuts used in ref. [19] were slightly different for exactly four-lepton and exactly three-lepton signatures, whereas in order to make a comparison between the four-lepton and  $\geq$  three-lepton signatures we are using the same set of cuts for both.

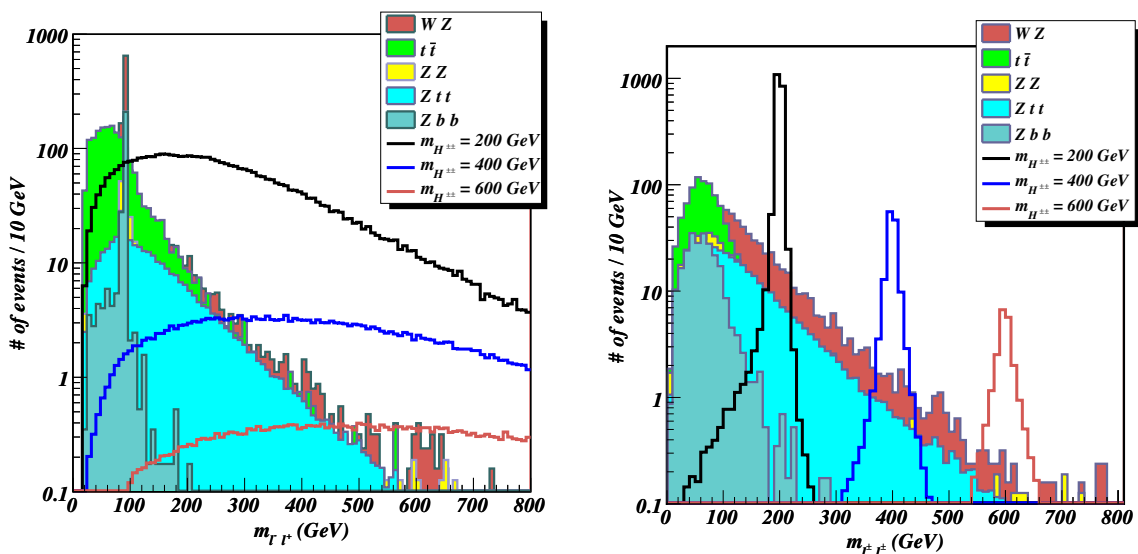
The effects of the cuts on signal and background events for the  $\geq 3\ell$  signature are given in table 5. It is evident that the discovery reach of the current signature is better than the  $4\ell$  signature.

Also shown in both tables 4 and 5 are the significance. As signal and background events become fewer after the cuts, it is necessary to employ Poisson statistics to estimate the significance of the signal. We use the significance estimator [54]

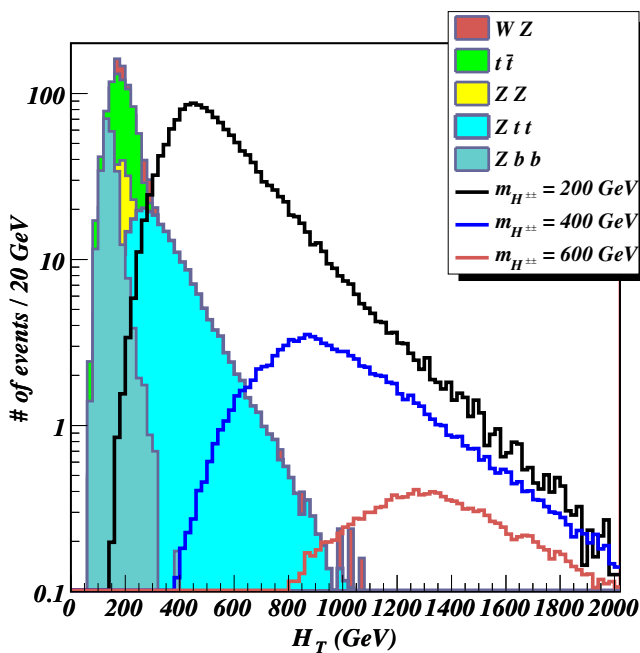
$$\mathcal{S} = \sqrt{2 \left\{ n_0 \ln \left( 1 + \frac{s}{b} \right) - s \right\}}, \tag{4.2}$$

where  $b$  is the expected number of background events and  $n_0$  is the number of observed events. Accordingly, the number of signal events is  $s = n_0 - b$ . This estimator is based on a log-likelihood ratio, and follows very closely the Poisson significance. In the limit of  $s/b \ll 1$ , it reduces to the simple estimator  $s/\sqrt{b}$ .

The distributions presented in figures 2, 3, and 4 are for the luminosity of  $\mathcal{L} = 10 \text{ fb}^{-1}$  and CM energy of 14 TeV at the LHC. In figure 2, we show the  $\cancel{E}_T$  distribution for both signal and background events. The background events concentrate at lower  $\cancel{E}_T$ , whereas the signal events extend to the higher region as they contain more energetic neutrinos coming from the singly charged Higgs bosons. In figure 3, we show two dilepton invariant mass distributions. As can be seen in the opposite-sign dilepton invariant mass distribution (left panel), the event distribution tends to peak around the  $Z$  mass as the lepton pairs mostly originate from the decay of the  $Z$  boson. These backgrounds can be readily reduced by imposing the  $Z$  window cut on the opposite-sign dilepton invariant mass. On the other



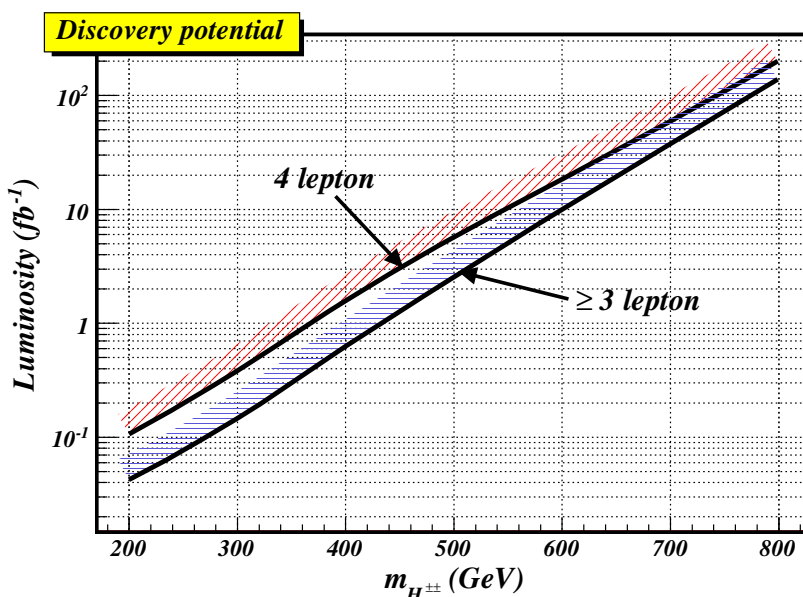
**Figure 3.** (a) Left panel: opposite-sign dilepton invariant mass distribution, (b) Right panel: same-sign dilepton invariant mass distribution, for both signal and background events.



**Figure 4.** Total transverse energy ( $H_T$ ) distribution for signal and SM background events.

hand, the same-sign dilepton invariant mass distribution peaks around the doubly charged Higgs mass whereas the SM processes form a continuous background, as shown in the right panel of figure 3.

Finally we show the total transverse energy distribution in figure 4. The  $H_T$  distribution peaks around the total mass of the heavy particles produced in the hard process. Hence this variable serves as a very useful discriminator between the signal and SM back-



**Figure 5.** Luminosity required for a  $5\sigma$  discovery of the doubly charged Higgs boson as a function of its mass at the LHC. The two curves correspond to the exactly 4-lepton signature and the  $\geq 3\ell$  signature, respectively.

grounds, especially for relatively heavy doubly charged Higgs masses. We emphasize that we have performed the first study of the dependence of the three-lepton signature on the parameter  $H_T$ . It is evident that a clear signal for  $H^{\pm\pm}$  can be obtained by using a cut on  $H_T$  to reduce backgrounds, even before plotting the dilepton invariant mass distribution (the latter providing information on  $M_{H^{\pm\pm}}$ ).

## 5 Discussions and summary

In this paper we have analyzed the leptonic signatures of the production of a doubly charged Higgs boson at LHC. For this purpose we have used CalcHEP to generate the signal events, and then interfaced it with PYTHIA . For more realistic estimates of signal and background events, we have used fast ATLAS detector simulator ATLFast . We have also included relevant K-factors for both signal and backgrounds in our analysis.

Using the significance estimator, we have estimated the LHC discovery potential for the doubly charged Higgs boson in the 4-lepton mode from the pair production only and the  $\geq 3$  lepton mode from the inclusive production, i.e., both  $pp \rightarrow H^{++}H^{--}$  and  $pp \rightarrow H^{\pm\pm}H^\mp$ . We have performed the first simulation of the  $\geq 3$  lepton channel. Our result is shown in figure 5, where the luminosity required to make a  $5\sigma$  discovery of the doubly charged Higgs boson is plotted as a function of its mass. It is clear that the discovery potential for  $H^{\pm\pm}$  at the LHC through the  $\geq 3\ell$  mode is significantly better than the 4-lepton mode. For an integrated luminosity of  $10 \text{ fb}^{-1}$ , for example, one detector at LHC alone can reach  $\sim 600 \text{ GeV}$  for the former and  $\sim 550 \text{ GeV}$  for the latter.

In our analysis of multi-lepton signatures we have not considered the QCD background where a jet is misidentified as a lepton. Although the probability of misidentification is quite small [39], the QCD production cross-sections are many orders of magnitude larger than the multi-lepton ( $3\ell$  and  $4\ell$ ) cross-sections and hence can contribute to the backgrounds. Importantly, the QCD background for the four-lepton signal will be smaller than that for the three-lepton signal. Hence the inclusion of the QCD background would introduce a systematic error into the estimates given in figure 5, which could alter the significance of our results. In an actual experiment, the QCD background can be estimated from the data. For a more realistic study, one should do a full detector simulation, optimize the cuts, and take into account the statistical and systematic uncertainties. We hope that this study will motivate our experimental colleagues at hadronic colliders to update their analyses by considering the following points:

- *Tevatron*: Include the process  $p\bar{p} \rightarrow H^{\pm\pm}H^{\mp}$  in the analysis when searching for the  $\geq 3\ell$  signature.
- *LHC*: Search for the  $\geq 3\ell$  signature to increase the LHC discovery reach of the doubly charged Higgs boson.

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