LHC Run-I constraint on the mass of doubly charged Higgs bosons in the same-sign diboson decay scenario

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In this Letter, we study the latest bound on the mass of doubly charged Higgs bosons, \(H^{\pm\pm}\), assuming that they dominantly decay into a diboson. The new bound is obtained by comparing the inclusive searches for events with a same-sign dilepton by the ATLAS Collaboration using the latest 20.3 fb\(^{-1}\) data at the LHC 8 TeV run with theoretical prediction based on the Higgs triplet model with next-to-leading order QCD corrections. We find that the lower mass bound on \(H^{\pm\pm}\) is about 84 GeV.

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I. INTRODUCTION

Recently, the ATLAS Collaboration has released the new results for the inclusive searches for events with a same-sign dilepton by using the 20.3 fb\(^{-1}\) data at the 8 TeV run of the LHC [1]. They improve the previous results based on the 4.7 fb\(^{-1}\) data at the 7 TeV run [2]. From non-observation of any excess from the standard model (SM) background, upper limits at the 95% confidence level (CL) on the fiducial cross section have been obtained for inclusive production of the same-sign dilepton from the non-SM contribution.

One of the most interesting applications of these results is to obtain a constraint on the parameter space for physics related to doubly charged Higgs bosons \(H^{\pm\pm}\). In various exotic models beyond the SM, \(H^{\pm\pm}\) are predicted to exist, e.g., in the left-right symmetric model [3], in models with the type-II seesaw mechanism [4], and in neutrino mass models via quantum effects [5]. In this Letter, we focus on \(H^{\pm\pm}\) in the Higgs triplet model (HTM) [4], where the Higgs sector is composed of an isospin doublet Higgs field with the hypercharge \(Y = 1/2\) and a triplet field with \(Y = 1\). In the HTM, two decay modes are allowed for \(H^{\pm\pm}\), i.e., decays into the same-sign dilepton and the same-sign diboson.\(^1\)

If the same-sign dilepton decay is dominant, the most stringent lower limit on the mass of \(H^{\pm\pm}\) has been obtained to be about 550 GeV [1] at the LHC.

On the other hand, searches for \(H^{\pm\pm}\) in the same-sign diboson decay mode are of distinct importance. The detection of interactions to weak gauge bosons can probe that \(H^{\pm\pm}\) come from Higgs fields with a non-trivial isospin charge. When the same-sign diboson decay is dominant, the mass bound given in the above is no longer applied. In our previous publications [7, 8], we have performed analyses to obtain the mass bound of \(H^{\pm\pm}\) in the diboson decay scenario in the HTM. By using the results on the inclusive searches for events with a same-sign dilepton at the LHC [2], the obtained mass bound of \(H^{\pm\pm}\) has been \(m_{H^{\pm\pm}} \gtrsim 60\) GeV [8]. In this Letter, we update our analysis based on the new data in Ref. [1], and revise the mass bound of \(H^{\pm\pm}\) in the diboson decay scenario.

II. ATLAS NEW RESULTS AT THE 8 TEV RUN

In Ref. [1], the inclusive searches for events with a same-sign dilepton have been performed by the ATLAS Collaboration by using the full data set at the 8 TeV run of the LHC. Events which contain a same-sign dilepton have been collected with the selection cuts of (i) \(p_T > 25\) GeV for the leading transverse momentum \(p_T\) lepton, (ii) \(p_T > 20\) GeV for the sub-leading \(p_T\) lepton, (iii) \(|\eta| < 2.5\) for both leptons where \(\eta\) represents the pseudorapidity and (iv) an invariant mass cut of \(M_{\ell\ell} > 15\) GeV. To reduce background from Z boson decays, (v) events with an

\(^1\) If \(H^{\pm\pm}\) are heavier than singly charged scalar bosons \(H^\pm\), \(H^{\pm\pm}\) can also decay into \(H^\pm W^\pm\) [6].
opposite-sign same-flavor dilepton whose invariant mass satisfies $|M_{\ell\ell} - m_Z| < 10$ GeV are rejected. In addition, in the $e^\pm e^\pm$ channel, (vi) events with a same-sign dielectron in the mass range between 70 GeV and 110 GeV are vetoed to use events in this region as a control sample to estimate the SM background. Total numbers of the collected events and invariant mass distributions are in good agreement with the prediction by the SM, and therefore upper limits on the cross section from the non-SM contribution are obtained for the fiducial region defined above.

### III. LIMIT ON $H^{\pm\pm}$ IN THE DIBOSON DECAY SCENARIO

The experimental limits on the fiducial cross section can be compared with the theoretical prediction calculated as

$$\sigma_{\text{fid}} = \sigma_{\text{tot}} \cdot B \cdot \epsilon_A,$$

where $\sigma_{\text{tot}} \cdot B$ is (sum of) the total cross section times branching ratio for the process giving the same-sign dilepton signal from the new physics model, and $\epsilon_A$ is the factor of efficiencies of the acceptance and kinematical cuts. We evaluate the fiducial cross section for the process with the same-sign dimuon, $\mu^+\mu^\mp$, in the final state via $H^{\pm\pm} \rightarrow W^{(*)\pm}W^{(*)\mp}$ in the HTM. The other channels, such as $e^\pm e^\mp$ and $\mu^\pm \mu^\mp$ turn out to give weaker bounds than the $\mu^\pm \mu^\mp$ channel. In the following discussion, we assume that the branching ratio of the diboson decay mode is 100%. The branching ratio for the $H^{\pm\pm} \rightarrow W^{(*)\pm}W^{(*)\mp} \rightarrow \mu^\pm \mu^\mp \nu\nu$ channel is explained in details in Ref. [8].

The dominant production processes of $H^{\pm\pm}$ at the LHC are (a) $pp \rightarrow H^{++}H^{--}$, (b) $pp \rightarrow H^{++}H^-$, and (c) $pp \rightarrow H^+H^-$, where $H^{\pm\pm}$ are the singly charged Higgs bosons which is also introduced in the HTM. The total cross sections for these processes have been calculated up to the next-to-leading order (NLO) in perturbative QCD [10]. Numerical predictions at the LHC with various collision energies can be found in Ref. [8]. We assume that the mass of $H^{\pm\pm}$ is the same as that of $H^{\pm\pm}$ for simplicity.

In this Letter, efficiencies for the acceptance and kinematical cuts are estimated by using MadGraphs [11] for each production process at the parton level in the leading order. Because we consider only inclusive production of a pair of same-sign muons, and do not count the other particles, the cuts (v) and (vi) explained in the last section are omitted. In Table I we summarize the total cross sections, branching ratio and the efficiencies for $m_{H^{\pm\pm}} = 50$ GeV to 100 GeV. By combining them, the fiducial cross section for the inclusive $\mu^\pm \mu^\mp$ production is calculated as

$$\sigma_{\text{fid}}(\mu^\pm \mu^\mp) = \left[\sigma_a \cdot \left(2\epsilon_a - \epsilon_a^2 B_{\mu\mu}\right) + \sigma_b \cdot \epsilon_b + \sigma_c \cdot \epsilon_c\right] \cdot B_{\mu\mu},$$

where $\sigma$, $\epsilon$ are the total cross sections, efficiencies for the processes (a), (b) and (c), respectively, and $B_{\mu\mu} = B(H^{\pm\pm} \rightarrow \mu^\pm \mu^\mp \nu\nu)$. The results for the fiducial cross sections are also summarized in Table I.

| $m_{H^{\pm\pm}}$ (GeV) | 50  | 60  | 70  | 80  | 90  | 100 |
|------------------------|-----|-----|-----|-----|-----|-----|
| $\sigma_{\text{tot}}^{NLO}(pp \rightarrow H^{++}H^{--})$ | 8.52 | 3.57 | 1.93 | 1.16 | 0.744 | 0.501 [pb] |
| $\sigma_{\text{tot}}^{NLO}(pp \rightarrow H^{++}H^-)$ | 10.6 | 4.47 | 2.36 | 1.40 | 0.891 | 0.598 [pb] |
| $\sigma_{\text{tot}}^{NLO}(pp \rightarrow H^+H^-)$ | 6.71 | 2.73 | 1.40 | 0.803 | 0.498 | 0.326 [pb] |
| $B(H^{\pm\pm} \rightarrow \mu^\pm \mu^\mp \nu\nu)$ | 2.22 | 2.21 | 1.21 | 1.16 | 0.98 | 0.61 |
| $\epsilon_a(pp \rightarrow H^{++}H^{--})$ | 5.1  | 9.9  | 16.  | 21.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  |
| $\epsilon_a(pp \rightarrow H^+H^-)$ | 4.9  | 9.9  | 15.  | 21.  | 22.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  |
| $\epsilon_a(pp \rightarrow H^+H^0)$ | 4.7  | 9.7  | 15.  | 21.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  | 23.  |

TABLE I: Table of the total cross sections [8] for $H^{++}H^{--}$, $H^{++}H^-$ and $H^+H^-$ processes, branching ratio of $H^{\pm\pm}$ into a same-sign dimuon [8], and the acceptance and cut efficiencies for $\mu^\pm \mu^\mp$ searches at the LHC with 8 TeV for $m_{H^{\pm\pm}} = 50$ GeV to 100 GeV. Efficiencies include acceptance cuts for $p_T$, $\eta$ of muons, and the invariant mass cut $M_{\mu\mu} > 15$ GeV. The resulting fiducial cross section is also listed.

Now, we are ready to compare the fiducial cross sections for the inclusive $\mu^\pm \mu^\mp$ production via the diboson decay of $H^{\pm\pm}$ at the LHC. In Fig. 1 the fiducial cross section for the $\mu^\pm \mu^\mp$ events is plotted as a function of $m_{H^{\pm\pm}}$. Red band shows the NLO prediction, where its width indicates 5% uncertainty from scale variation and errors from parton

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2 This scenario can be realized by taking the vacuum expectation value of the triplet field to be larger than about $10^{-4}$ GeV [8].
FIG. 1: The fiducial cross section for the $\mu^\pm \mu^\pm$ channel at the LHC 8 TeV collision as a function of $m_{H^{\pm\pm}}$. The green dashed horizontal line shows the 95% CL upper limit from the ATLAS data of the integrated luminosity to be 20.3 fb$^{-1}$. Red shaded band shows the NLO prediction with 5% uncertainty. Details can be found in Table I.

distribution functions [12]. The green dashed horizontal line shows the 95% CL upper limit obtained by the ATLAS Collaboration,

$$\sigma_{95}^{\text{fid}}(\mu^\pm \mu^\pm, M_{\mu\mu} > 15 \text{ GeV}) = 16 \text{ [fb]}.$$

(3)

By comparing them, we find that doubly charged Higgs bosons with $m_{H^{\pm\pm}} \lesssim 84$ GeV are excluded in the diboson decay scenario. For the reference, the experimental limits for the other decay channels are reported as $\sigma_{95}^{\text{fid}}(e^\pm e^\pm, M_{ee} > 15 \text{ GeV}) = 32 \text{ [fb]}$ and $\sigma_{95}^{\text{fid}}(e^\pm \mu^\pm, M_{e\mu} > 15 \text{ GeV}) = 29 \text{ [fb]}$, while theoretical estimations for these channels are comparable with the $\mu^\pm \mu^\pm$ channel in the mass range of $m_{H^{\pm\pm}} \lesssim 90$ GeV [8]. Thus, the limits by these channels are negligible.

IV. CONCLUSION

We have studied the latest mass bound on the doubly charged Higgs bosons in the diboson decay scenario in the HTM. The new limit has been obtained by comparing the inclusive searches of events with a same-sign dilepton by the ATLAS Collaboration using the latest 20.3 fb$^{-1}$ data set at the LHC 8 TeV run [1] with theoretical prediction which includes the production cross section with NLO QCD corrections, branching ratio with interference effects, and efficiencies for the acceptance and kinematical cuts [8]. The lower bound has been revised to be $m_{H^{\pm\pm}} \gtrsim 84$ GeV.

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