PROCEEDINGS OF SCIENCE

Search for doubly charged Higgs boson production in multi-lepton final states using 139 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Blaž Leban*, **on behalf of the ATLAS Collaboration**

Jožef Stefan Institute,
Jamova cesta 39, Ljubljana, Slovenia
Faculty of Mathematics and Physics, University of Ljubljana,
Jadranska ulica 19, Ljubljana, Slovenia

E-mail: blaz.leban@cern.ch

A search for pair production of doubly charged Higgs ($H^{\pm\pm}$) bosons, each decaying into a pair of prompt, isolated, and highly energetic leptons with the same electric charge, is presented. The search uses the proton–proton collision data sample at the centre-of-mass energy of 13 TeV corresponding to 139 fb^{-1} of integrated luminosity recorded during Run 2 at the Large Hadron Collider by the ATLAS detector. This analysis focuses on same-charge leptonic decays, $H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}$, where $\ell, \ell' = e, \mu, \tau$ in two-, three-, and four-lepton channels, but only considers final states which include electrons or muons. No evidence of signal is observed. Corresponding limits on the $H^{++}H^{--}$ production cross-section and consequently a lower limit on $m(H^{\pm\pm})$ are derived at 95 % confidence level. Under the assumption that the branching ratios to each of the possible leptonic final states are equal, the observed lower limit on the mass of a doubly charged Higgs boson is 1080 GeV, which represents an improvement over previous limits.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

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PoS(ICHEP2022)1081

1. Introduction

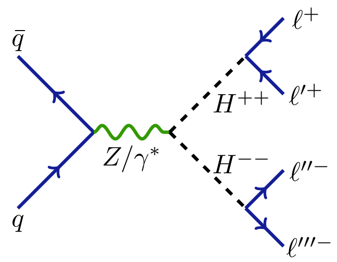


Figure 1: Feynman diagram of the pair production process $pp \to H^{++}H^{--}$. Note that only electrons and muons in the final states are considered in this analysis. Taken from Ref. [1].

The Standard Model (SM) assumes neutrinos to be massless, but experimental evidence of neutrino oscillations [2] implies that at least two neutrino flavours have small but non-zero masses. The discovery of neutrino oscillations automatically demands for an extension of the SM. The ATLAS search [1], presented at the conference, tests one of the simplest known ways to account for the smallness of neutrino masses, namely the type-II seesaw mechanism, which extends the SM by introducing a single scalar triplet H. Furthermore, the analysis focuses on the left-right symmetric model, which extends the SM gauge group to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Neutrino masses are generated through Yukawa couplings between the SM leptonic doublet and the scalar triplets $H_{L,R} = (H^0, H^\pm, H^{\pm\pm})_{L,R}$, where H^0, $H^\pm$ and $H^{\pm\pm}$ are the usual SM Higgs boson, the singly and the doubly charged Higgs bosons, respectively. Consequently, new charged Higgs bosons could be produced in EW processes in proton–proton (pp) collisions at the Large Hadron Collider (LHC). This ATLAS analysis searches for signs of the $H^{\pm\pm}$ dominant Drell–Yan production mechanism

$$pp \to Z/\gamma^* \to H^{++}H^{--} \to \ell^+\ell'^+\ell''^-\ell'''^-, \quad \text{where} \quad \ell, \ell' = e, \mu, \tau. \tag{1}$$

This search focuses on small vacuum expectation value of the left-right spontaneous symmetry breaking, v_Δ, which means that only decays into a pair of prompt, isolated, and highly energetic same-charge leptons, irrespective of flavour combination, are possible, thus also the Lepton Flavour Violation (LFV) is allowed. Since such events are produced very rarely in pp collisions by SM processes, same-charge lepton pairs represent a striking signature for new physics. Two-lepton, three-lepton, and four-lepton final states that include electrons or muons are considered. Branching fractions of decays into all possible combinations of standard model leptons are assumed equal, $\mathcal{B}(H^{\pm\pm} \to \ell^\pm\ell'^\pm) = 1/6$. Finally, the search can be reinterpreted in a few more models that include similar $H^{\pm\pm}$ particles.

2. Recorded data and background modelling

The ATLAS detector [3] is the largest multipurpose detector at the LHC facility, with a forward-backward cylindrical symmetry. It covers almost the whole solid angle around the collision point. It consists of multiple detector subsystems, starting from beam-line outwards with the inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and finally, a muon spectrometer as the outermost detector that also incorporates three large superconducting toroidal magnets.

This analysis uses data from pp collisions at $\sqrt{s} = 13$ TeV, collected with the ATLAS detector in the full Run 2 period of the LHC and amounts to 139 fb^{-1}.

Monte Carlo (MC) event generators were used to model signal and background events. Simulated background samples include Drell–Yan ($q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$), diboson ($WW$, WZ, ZZ), single top quark and top quark pair ($t\bar{t}$) production processes. Simulated samples provide estimation for both the irreducible (real leptons) and reducible (misidentified leptons) backgrounds.

3. Analysis strategy

Three distinct types of regions are defined for this search: *control regions* (CR), *validation regions* (VR), and *signal regions* (SR). CRs are used to constrain the yields of the simulated MC backgrounds. The background model is verified in the VRs. SRs are optimized to search for same-charge lepton pairs and are used to compare data to the expected signal-and-background hypothesis using the statistical methodology described in Section 4.

The main variable used to distinguish between CRs, VRs and SRs is the invariant mass of the two same-charge leptons with the highest p_{T} in the event, $m(\ell^{\pm}, \ell'^{\pm})_{\mathrm{lead}}$, where $\ell, \ell' = e,\ \mu$.

SRs, independently of the lepton multiplicity and flavour combination, require $m(\ell^{\pm}, \ell'^{\pm})_{\mathrm{lead}}$ to be above 300 GeV. To maximize the sensitivity, additional requirements are imposed on same-charge lepton pairs in order to exploit both the boosted decay topology of the $H^{\pm\pm}$ resonance and the high energy of the decay products. The CRs and VRs either span a lower $m(\ell^{\pm}, \ell'^{\pm})_{\mathrm{lead}}$ interval or require other orthogonal selections.

4. Statistical analysis and results

The maximum-likelihood fit considers the leading lepton pairs' invariant mass distribution $m(\ell^{\pm}, \ell'^{\pm})_{\mathrm{lead}}$ in all two- and three-lepton control and signal regions, while the single-bin event yield in four-lepton regions is used. The likelihood is the product of the Poisson probability density function describing the observed number of events and Gaussian distributions to constrain the nuisance parameters associated with the systematic uncertainties.

Various sources of theoretical and experimental uncertainties that affect both background and signal predictions were taken into account. When performing the statistical analysis, the impact of systematic uncertainties on both the total event yields as well as the changes in the shape of kinematic distributions is accounted for. The fit reduces the systematic uncertainties and makes yields compatible with their SM predictions within uncertainties, see Figure 2.

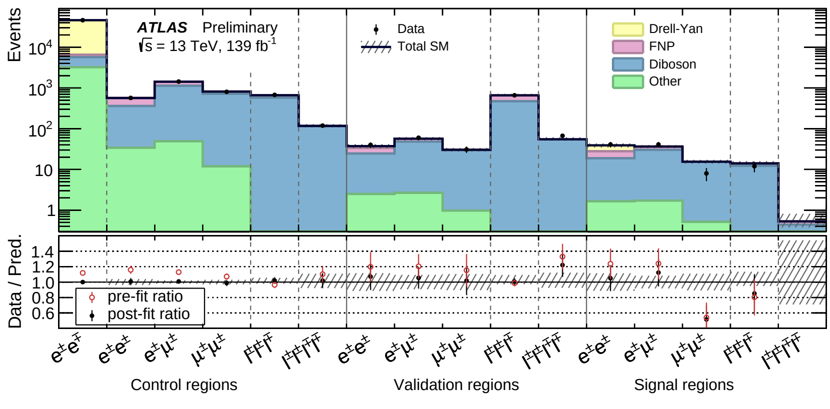
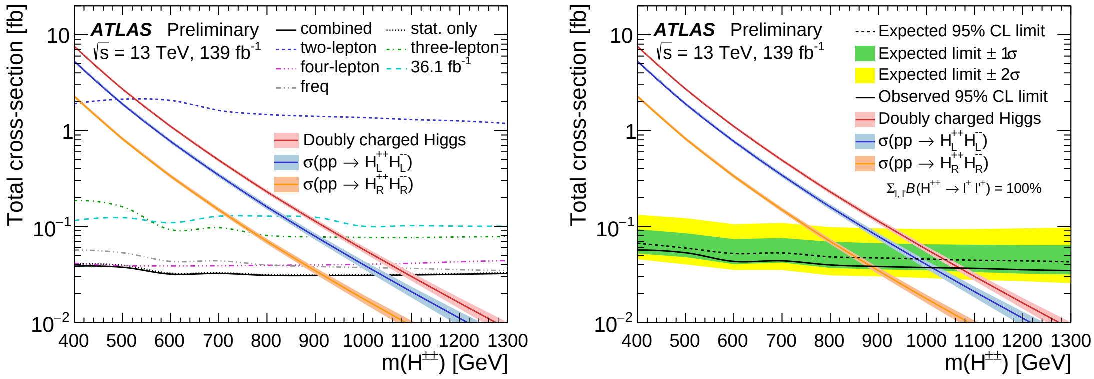


Figure 2: The numbers of observed and expected events in the CRs, VRs, and SRs for all channels. The hatched bands include all post-fit systematic uncertainties with the correlations between various sources taken into account. The error bars show statistical errors. FNP refers to the fake/non-prompt lepton background. Top quark and multiboson process backgrounds are merged under the "Other" category. The lower panel shows the ratio of the observed data to the estimated SM background. Taken from Ref. [1].

In absence of a significant deviation from expectations, 95 % CL limits were derived. The observed lower mass limits vary from 520 GeV to 1030 GeV, depending on the lepton multiplicity channel and reaches 1080 GeV when combining all three channels. This agrees well with the expected exclusion limit of 1040^{+40}_{-60} GeV. The limit obtained from the four-lepton final state is the most sensitive and drives the combined result. A comparison between various limits obtained from this measurement is presented in Figure 3.



(a) **(b)**

Figure 3: Various observed and expected 95 % CL upper limits on the $H^{\pm\pm}$ pair production cross-section as a function of $m(H^{\pm\pm})$, assuming $\sum_{\ell\ell'} \mathcal{B}(H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = 100\,\%$, where $\ell, \ell' = e, \mu, \tau$. The theoretical signal cross-section predictions, given by the NLO calculation [4], are shown as blue, orange and red lines for the $H_L^{\pm\pm}$, $H_R^{\pm\pm}$, and a sum of both, respectively. (a) The dashed blue, green, and purple lines indicate the observed limit using the two-, three-, and four-lepton exclusive final states, respectively. The black lines show the combined observed limit using the asymptotic approximation for statistical only fit (dotted) and stat. + sys. fit (solid). The gray line shows the limit obtained using the pseudo-experiments, and the cyan dashed line shows the combined observed limit obtained analysing first 36.1 fb^{-1} of Run 2 [5]. (b) The shaded bands correspond to ±1 or 2σ uncertainty around the combined expected limit, as estimated using the frequentist approach. Taken from Ref. [1].

5. Conclusion

The ATLAS detector at the LHC was used to search for $H^{\pm\pm}$ bosons in the same-charge two-lepton invariant mass spectrum, using final states containing electrons and muons in the $\sum_{\ell\ell'} \mathcal{B}(H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = 100\,\%$ regime regime. The search was performed with 139 fb^{-1} of data from pp collisions at $\sqrt{s} = 13$ TeV, recorded during the Run 2 data-taking period. No significant excess above the SM prediction was found. The observed combined lower limit on the $H^{\pm\pm}$ mass is 1080 GeV and is consistent with the expected limit of 1040^{+40}_{-60} GeV.

References

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