European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

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Referee report of doctoral dissertation of Ms. Camilla Galloni titled “Search for Heavy Resonances Decaying into Two Higgs or into Higgs Boson and a W or Z Boson in the $q\bar{q}\ \left(b\bar{b}\right)\tau^{+}\tau^{-}$ Final state with the CMS Detector”.

Standard Model (SM) of particle physics is the current theory of microworld. It combines the Glashow-Weinberg-Salam model of electroweak interactions with Quantum Chromodynamics, the theory of strong interactions. The SM was derived in the mid 1970s and since then has undergone massive experimental stress tests. The recent discovery of Higgs Boson by ATLAS and CMS collaborations completes the particle content of the SM. Despite these and other successes the SM it cannot be consider the final theory of the microworld. It does not contain gravity which becomes relevant at the Planck scale, it does not explain the hierarchy problem. Moreover, the SM disagrees with some experimental observations such as matter-antimatter asymmetry. Forthermore, it does not describe the dark matter or dark energy nor does it explain the origin of neutrino masses. Given all the flows of the SM it is not a surprise that searching for the theories beyond the SM, called New Physics (NP) or Beyond Standard Model (BSM) is the main task of LHC experiments. Ms. Galloni has pursued exactly this path in her research activities.

Ms Galloni has focused on searching for New Physics, which could manifest itself as a resonant in the HH, WH and ZH final states using data collected in Run1 and Run2 of LHC. Such large amount of data allows to set very strong limits on the possible mass scale of NP.

The dissertation consists of 8 chapters, including Introduction and Conclusions and together with bibliography spans over 198 pages. This makes it a rather long dissertation; however, the size is justified given the number of results that are. After a very short introduction the SM is described followed by the chapter containing relevant extensions of the SM to the analysis described in this dissertation. Chapter 4 contains the description of the Compact Muon Solenoid (CMS) detector and the accelerator complex at CERN.

Chapter 5 defines objects that are used in the data analysis. Chapter 6 and 7 describe the analysis with Run1 and Run2 data respectively, while chapter 8 concludes the dissertation. In the following review, I will provide detailed comments for each of the chapters.

Chapter 1 is a nice introduction to the whole text. It allows the reader to set his/hers mind and understand the main purpose of the dissertation. Ms. Galloni puts the SM in the historical context, defines the main objective of the research and data that will be used. I do not have any criticism about this chapter.

The second chapter is devoted towards the description of the SM. It starts by defining the particle content of the SM. Ms. Galloni correctly groups the spin half particles into two categories, which are Lepton and Quarks and discusses their properties and generations. It is worth mentioning that Ms. Galloni when providing units uses the convention with c=1, which she did not state explicit in the text. Then she moves to describe the forces, starting from the strong and finishing on the electroweak one. I think the information that Ms. Galloni presented in this part is well balance and adequate for an experimental PhD dissertation. The only minor criticism would be lack of introduction of CKM matrix, which is relevant for the weak interactions. The next section is devoted description of the Higgs mechanism. Section 2.4 presents the current experimental status of the Higgs measurements. I very much appreciate these section as it is relevant to the dissertation, however it would be nice to summarize the properties of gauge bosons(W,Z) as well since they are relevant in the same manner as is the Higgs.

Overall Chapter 2 shows a very good balance between the length and the necessary details. These shows undoubtedly that Ms. Galloni mastered the theoretical details needed for an experimental physicist.

Chapter 3 presents extensions to the SM, that can produce possible signals, which are search in this dissertation. It starts again with repetition why the SM cannot be considered a final theory. It is true Ms. Galloni goes into more details (for example in the radiative corrections to the Higgs mass), but in general reader get the impression that this was already said in previous chapters. In addition, the list of flaws of SM is incomplete. Ms. Galloni does not mention for instance neutrino masses.

Section 3.1 discusses the extensions of the SM by introduction of extra dimensions. These types of models have been on the market since 1920, when Kaluza and Klein attempted to provide unification of electromagnetic and gravitational interactions. The general feature of this and similar models with extra dimensions is that the gravity can be propagated to the extra dimensions that are not accessible to other interactions. This mechanism explains why the gravity appears to be such a weak force compared to other ones. The model picked by Ms. Galloni has five dimensions. She later introduces the metric of these five-dimension space, defines the energy scale and derives two types of particles: graviton and radion. Moreover, Ms. Galloni shows their interaction with SM particles (eq. 3.11) and presents the production mechanism with calculated cross-sections.

The BSM extensions discussed by Ms. Galloni contain also the simplified models involving extra spin -1 resonances. The framework of simplify models is chosen here with good reason. New spin-1 resonances appear in so many models it is hard or even impossible to study all of them. The simplified models allow for a recasting of the results on any model that is of interest to the theory community. The last small section of this chapter presents the current situation of searches for diboson resonances at LHC. I find it a very nice introduction to research that will be described in Chapters 5 and 6. My main criticism towards this chapter would be lack of proper citations to theory papers. For example, when discussing the matter and anti-matter asymmetry and CP violation there is no reference to Sakharov paper. From editorial point of view in line 512 the Figure 3.1 is not correctly referenced (word "Fig." is missing) and lines 743 and 744 break in the middle of the line.

Chapter 4 presents the LHC accelerator and CMS detector and is a standard part of experimental dissertations. The accelerator part is keep short (1.5 pages), while the detector part is explained in greater details. Writing this chapter is not always easy, as there is a serious risk of falling into to many technical details. This is not the case with Ms. Galloni. The chapter is well balanced and reader can learn about the CMS detector without the fear of being overwhelmed. From Prof. Kilminster, I know that Ms. Galloni has performed pixel detector position resolution measurement, which is shown in Fig. 4.6. Without information from Prof. Kilminster I would not know it is her original input in the detector studies, which is a shame as the work seems very interesting and deserves recognition. Ms. Galloni uses in some places jargon, which is probably only understandable inside CMS collaboration. For example in line 812, she writes: "data collected and certified in 2016". Reader needs to guess at this point what a certified data is. In addition, in line 1066 a copy paste error "system allows to allows" should be fix.

The description of experimental tools used by Ms. Galloni is given in Chapter 5. It is one of the biggest chapter in the dissertation and has over 50 pages. It starts by describing the tracking algorithm used by CMS collaboration. From the reconstructed tracks vertexes are formed. Here the description of the algorithm is bluaery at best. For instance, from the sentence: "For each candidate, a weight w_i close to 1 (0) is assigned to each track i, which reflects the likelihood that it genuinely belongs to the vertex" is not understandable. I think the level of details Ms. Galloni tried to present in the section is not needed and only confuses the reader. She later defines the particle-flow algorithm and muon and electron candidate reconstruction and selection requirements for them.

Ms. Galloni defines so-called modified lepton isolation, which aims to discriminate between the QCD processes and leptons. In contrast to the "standard" lepton isolation the modified one shows over two times higher efficiency (Fig. 5.5) for tau lepton decays for small angular distance, which has a direct impact on the searched signal efficiency. The dissertation later describes the jet reconstruction. This section shows the depth of knowledge Ms. Galloni has, as all the important ingredients such as different jet algorithms (inclusive-k_T , Cambrige-Aachen, anit-k_T), energy calibration, pileup background and b-tagging are explained. After this, Ms. Galloni describes the tau lepton properties. Their reconstruction is not easy task at LHC experiments. Firstly, taus are not stable particles and decay in the detector forming a secondary vertex. Secondly, due to their large mass they are the only leptons that decay hadronically, with many possible final states. Lastly when they decay at least one neutrino in the final state is present, which makes reconstructing their invariant mass an impossible task. The leptonic decays of taus are reconstructed with the standard electron and muon reconstruction algorithms, which were already described in previous section. The hadronic decays of taus are reconstructed with so-called hadron-plus-strip algorithm, which for Run2 is improved by adding the photons to the strip reconstruction. To reduce the jet misidentification to a tau lepton an Boosted Decision Tree is trained. Such approach is part of modern data analysis and shows that Ms. Galloni has all the necessary skills in performing this type of data analysis. Furthermore, Ms. Galloni describes the so-called boosted reconstruction, which is her own algorithm. Fig. 5.24 clearly shows the gain in performance of Ms. Galloni boosted algorithm compared to the "standard" one.

In summary, the Chapter 5 contains selection and algorithms developed by Ms. Galloni. It is worth pointing out that most of things that have been presented and done by Ms. Galloni can be reused in other analysis of the CMS collaboration. Form editorial point of view I have spotted a wrong citation formation in line 1168: "[80], [81], [85]."

Chapter 6 presents the experimental result of searches for a new resonance decaying to two Higgs bozons using 2012 CMS data. The problem is that Higgses have many different ways it can decay. Usually experimentalists are there face with a problem which final state use to get the best sensitivity. Ms Galloni has choosed one Higgs decays to two tau leptons while the other to two b quarks. For the tau leptons reconstruction Ms. Galloni has used developed by her "boosted" algorithm described in previous chapter. The mass regions scanned are 0.8-2TeV. For the b jets the standard algorithm is used described in Sec. 5.3.5.1.

To the selected candidates additional requirements are applied to reduce background from low-mass resonances. The requirements are implemented as cut and listed in Tab. 6.1. The backgrounds that are relevant for this analysis are: $t\bar{t}$, W+jets and Drell-Yan + jets. Ms. Galloni in a correct experimental manner tries to rely on MC simulations as little as possible. The data is checked with the MC using a looser selection (so called untagged events) and a very good agreement is found (Fig. 6.9 and Fig. 6.10). This is a very important step for experimental analysis and again show very good experimental skills of Ms. Galloni. Later systematic uncertainties are discussed. Unfortunately, the systematic section (Sec. 6.5) has is only one page long and reports only the size of the systematic but doesn't give any satisfactory description how the systematic was evaluated. It is true that in this type of analysis the systematic uncertainties are smaller compared to statistical uncertainty, however they should still be described in greater details. As a result of the analysis no access of signal has been observed (Fig. 6.13) and upper limits have been set. Again, I would appreciate a short description how systematic uncertainties enter in the CL_s calculation. The results of this chapter appear to be very solid and have been made public by CMS collaboration in the form of Physics Analysis Summary (PAS).

Chapter 7 describes an update of the analysis using 2016 data. The analysis has been refined in so many ways I will review it again step by step. Firstly, the search is extended by a process $pp \rightarrow VH \rightarrow q\bar{q}\,\tau\tau$. In addition the trigger requirements have been refined to coop with the higher centre-mass energy. In Section 7.3 Ms Galloni discussed refinements in the muon, jet and tau selections. Again, the data (with looser selection) is compared with the expected background from MC in Fig. 7.6-7.15 and very good agreement is observed. To further take the advantage of avaible signal and sideband regions have been defined. Different regions are dominated by different background/signals which allows more refine cross-checks of MC background simulations. Since we are on the considered background, also this section has been refined. It now includes additional sources. However, again the dominant background was found to be the top pair production. It is worth pointing out that the description of background modelling has improved dramatically. The mass shape is modelled with analytical function. This approach is superior to often used "template" fitting as it provides faster and more stable results. Ms. Gallani has considered wide range of analytic functions for fitting these distributions. I need to congratulate Ms. Galloni on the systematic section 7.6. Here in contrast to previous chapter the systematics are very well described. In addition Ms. Galloni references to Appendix A where she described how the systematic enter the CL_s calculation. Furthermore, the fit result of all nuisance parameters is presented (Fig. 7.30 and 7.31), and show a very good pull distributions, which reassures the reader about the validity of the analysis. Unfortunately no access of events above the SM expectations have been observed and upper limits have been set which later were interpreted in terms of simplified models. The results presented in this chapter have been send to journal publications with positive feedback of the referee and a fast publication is expected. I think this is the best chapter (and the most important one) of the whole dissertation. It shows a very original and mature analysis pefromed by Ms. Galloni. The only small criticism I have towards this chapter is a bit vague discussion about possible future improvements. Chapter 8 concludes the dissertation.

In summary, the dissertation of Ms. Galloni presents results from wide spread of areas. Starting from software development and finishing on the experimental data analysis. It clearly shows that Ms. Galloni is a mature and independent researcher. My comments about the dissertation are of editorial nature and do not change any of the scientific results or the conclusions of this dissertation. In addition, Ms. Galloni is the L3 convener at the CMS collaboration, which also show that her work has been recognized by collaboration.

Concluding, the doctoral dissertation of Ms. Galloni fulfills all the necessary legal and social requirements of such document and I recommend to allow its public defense.

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