The review of doctoral thesis

The author of the thesis: Kristina Mihule
The title of the thesis: Studies of Higgs boson in its decay to a pair of tau-leptons and search for excited tau-lepton with the ATLAS detector

In this thesis, studies about the production of a pair of tau leptons in proton-proton collisions within the ATLAS experiment at Large Hadron Collider are presented. Two physics analyses are described: the Higgs boson production and the search for an excited tau lepton. Both of these topics are very relevant. The accurate measurements of the Higgs boson properties and the search for new physics beyond the Standard Model are among the key tasks of the ATLAS experiment.

The thesis is divided in 10 sections and conclusion. There are also many appendices describing details of particular studies. In the initial sections, the author describes key ingredients of the ATLAS environment such as the LHC accelerator, the detector, the simulation of events and the reconstruction of basic physics objects used in both analyses. I think that more systematic description of the detector could have been done, e.g. granularity in $\eta \times \phi$ space is mentioned only for hadronic tile calorimeter. On the other hand, the physics objects are described in a good detail.

The middle part (Sec. 6-8) describes the key background ('fake events'), gives a general analysis flow, and describes a key di-tau mass reconstruction method used in both analyses. I think 'fakes' background estimation with the fake-factor method should have been explained and described in more detail (although some more information is given in Section 9 and 10). On the other hand, there is a nice overview of various existing methods for di-tau mass reconstruction.

In sections 9 a 10, both physics analyses are finally described. In Section 9, Higgs boson production in di-tau final state is presented. Here, only some very specific studies related to di-tau mass reconstruction are described (I assume these are the parts where the author directly contributed). I'm missing here the overall description of the analysis procedure, it's not even clear what is the goal of the measurement (is it the Higgs cross-section of the Higgs coupling?). This omission makes it harder to understand the importance of the presented studies, e.g. since there is no table or picture with the yields for different processes, it's not clear how significant is the $Z \to \tau\tau$ background.

In Section 10 is described the search for excited tau lepton. Here, the full analysis procedure is described and the author presents many detailed studies from various steps of the analysis which show that she was involved in many/all steps of the full analysis chain.

I list below a few specific questions and comments to the presented text:

- Missing Mass Calculator (Sec. 8.2.5): you mention that properties of decay products do not depend on tau-lepton origin and perform the parametrisations (at least some, e.g. Fig. 9.6) on $Z \to \tau\tau$ events. However, given the different type of origin particle

(Higgs is a scalar,spin-0 particle, while Z boson is a vector, spin-1 particle), I have a doubt about that, e.g. missing E_T distribution and consequently also the resolution (e.g. $P(\Delta R_{0(1)}^{vis,miss})$ on p.47) should be different for both cases. Was this studied?

- Fig.9.7: the result of the fit for $\Delta\phi < 2.25$ is 0.96 ± 6.35 according to the plot. The uncertainty is huge here and seems not consistent with the small uncertainties in the individual points. Can you explain?
- Fig. 10.8.: based on these plots, you decide to use Loose working point (WP) for taus. However, from Fig. 10.8d, it looks like Medium WP is a little bit better at high S_T values. Can you comment?
- $t\bar{t}$ control region (Sec. 10.8.2): using dilepton $e\mu + 2$ b-tagged jets as a control region could be problematic since it's a bit different from the signal region (instead of using taus, it's using light leptons, and also it's using b-tagging while the signal region is not). Can you comment on this? Also, it's known that the kinematic distributions for $t\bar{t}$ production show the slope for data/prediction ratio (you see this also in Fig. 10.31) due to missing higher-order terms in the signal prediction. From the text, it was not clear whether you take this into account (e.g. are you doing p_T reweighting?).
- Figure 10.23c: it seem p_T of the leading tau is greater than 70 GeV for all masses of excited tau lepton. Is there any reason why do you then require in the analysis that $p_T \geq 40$ GeV? The background could have been more suppressed with tighter cut.
- Figure 10.43: do you understand why p-value for background model depends slightly on signal strength μ_{SIG}?
- regarding the conclusions: my understanding is that in all results in Section 10, the fit in signal region was performed on simulated events (Asimov dataset). However, in conclusion the author says that 'No excess of events is observed, and no sign of excited tau-leptons was found in the analyzed data set'. This suggests that you ran on experimental data. Is this so? Or did you really run just on simulated data?

Unfortunately, I have to state that from a formal point of view the work is not at a good level. There are a lot of shortcomings, such as:

- relatively large amount of inaccurate, ambiguous statements, e.g. Fig. 9.1 holds at 13 TeV only, I assume; "fiducial and differential' (p.51) $\rightarrow$ both total and differential cross-section measurements could be fiducial, etc.
- bibliography: there are missing identifiers for some references, e.g. Ref.[101]-[104], which are CERN technical reports (I assume that these are ATLAS internal notes)
- figure style issues: e.g. style can be improved in many plots (not clear legends in many figures), Fig. 9.8 has a wrong label for y-axis, Fig. 9.31 has pictures of different size
- often referencing to image 'N+1' before image 'N', e.g. Fig. 10.20 is described before Fig. 10.19

- many small mistakes/typos, e.g. wrong reference to equation ('Eq. (eq:mmc:likelihood)') (p.69), Fig. 10.27 caption: '$Z\tau\tau$ CR' → 'Fakes SS CR', Tab. 10.8: the CR labels are wrong, 100 GeV → 200 GeV (p.111), 'Higgs filed' (p.7)

The thesis is written in English. It's difficult to understand some sentences due to their structure.

In summary, I state that the author described the experimental apparatus, the procedure, and the results of two physics analyses. These measurements contribute to knowledge in the particle physics. The thesis met its goals.

The author of this work is the primary co-author of the article about the production of the Higgs boson, which has already been published. The article regarding the search for excited tau-leptons passed through all the steps of the review procedure within the ATLAS experiment and was approved by the ATLAS collaboration for submission to a physics journal just yesterday. It should be noted here that the author made a significant contribution to the given analysis, which was performed within a small analyzing team.

Based on the above, I think that even if the formal presentation of the measurements is not at a very good level, the measurements themselves provide a contribution to the given field of science and that the author demonstrated the prerequisites for independent creative activity. Assuming a successful defense and answering my questions above, I **recommend** that the author be awarded with a PhD degree.

15.3.2023

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