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Referee's report on the Ph.D. thesis

Title: Vector Boson Scattering and ZZ Production at ATLAS Detector
Author: Ing. Ondřej Penc

The Ph.D. thesis presented by Ondřej Penc is dedicated to experimental studies of the four-lepton *ZZjj* electroweak production channel in proton-proton collisions at the center of mass energy $\sqrt{s}$ = 13 TeV measured by the ATLAS experiment at the Large Hadron Collider (LHC) at CERN. Although the measurement has a very clean final state with the two *Z* bosons (*ZZ*) decaying into four leptons and a pair of jets (*jj*), the measurement is very challenging due to its very small cross section. The topic of the thesis is of high scientific relevance for high energy physics community as it contributes to understanding the nature of electroweak symmetry breaking in the Standard Model (SM) of particle physics and searches of physics beyond the SM which are being carried out by the LHC experiments at unprecedented collision energies and luminosities.

The thesis consists of twelve chapters and an appendix which contains additional supporting figures and tables. After a short introduction in Chapter 1, Chapter 2 presents a motivation and a broader context of importance of the research carried out in the remaining parts of the thesis. Chapter 3 discusses in detail the operating principle of the LHC and the whole acceleration chain along with description of individual ATLAS subdetectors, trigger, data acquisition and luminosity measurement. The two following chapters, Chapter 4 and Chapter 5, contain description of experimental data, Monte Carlo samples and analysis workflow. Original contributions and main physics results achieved by the author are contained in Chapter 6 through Chapter 11. Chapter 6 gives details on event selection followed by background estimation in Chapter 7 and details on systematic uncertainties determination in Chapter 8 which are essential for the interpretation of final physics results. Chapter 9 – Chapter 12 conclude the thesis and contain the main physics results - determination of the electroweak cross section in the *ZZjj* channel along with the inclusive *ZZjj* production cross section and significance of rejection of the QCD-only hypothesis followed with discussion of these results in the context of other recent measurements.

From the formal point of view the thesis is well structured and written with acceptable number of typos. The figures, tables, references and the text itself are processed according to standards. However, I would like to note that in some parts of the thesis the author uses colloquial, informal language style which is not appropriate for the Ph.D. thesis. The level of details given in individual chapters could be also slightly better balanced. I think that Chapter 2 could benefit from a more solid theoretical description introducing e.g. the DGLAP equation, splitting functions or concepts of hadronization which are later only briefly mentioned in Chapter 4. In Chapter 3, the author gives details on the LHC beam parameters etc. which are

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not directly relevant to the topic of the thesis while in some other parts (Chapter 6 and following) the thesis would benefit from a more detailed description of individual steps and rather technical details which are sometimes difficult to follow (for a non-ATLAS person). For example, it could help to improve clarity of the thesis by describing in some more detail the main concepts and differences of the Monte Carlo generators SHERPA and MadGraph used throughout the thesis or by providing more details on the Jet Vertex Tagger (Chapter 6.3.4) and its parameter choice to name some.

The used experimental methods are state of the art in high energy physics and I was very glad to see that the author showed that he is also able to contribute with his own approach by using the Scikit learn toolkit instead of the more conventional TMVA toolkit to optimize the selection criteria. The data analysis and systematic uncertainties evaluation meets high standards and the obtained results of the electroweak and inclusive *ZZjj* production cross sections and the significance of rejection of the QCD-only hypothesis in this production channel are within uncertainties in agreement with other available measurements by the ATLAS and CMS collaborations and SM model predictions.

In summary, I conclude that the Ph.D. thesis of Ondřej Penc is of a high importance for the field of high energy physics and the thesis contains original physics results achieved by the author. The author proved that he is able to efficiently work in the large international team as well as able to perform independent and complex analysis of experimental data. The results are an inherent part of two ATLAS publications in high profile journals (Phys. Rev. D and an article submitted to Nature Physics). The thesis manuscript thus fulfills all requirements for the Ph.D. thesis. I recommend the thesis to be accepted by the committee and after successful defense to award Ondřej Penc the Ph.D. degree.

May 10, 2021

RNDr. Jana Bielčíková, Ph.D.
Nuclear Physics Institute
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Questions to the author of the thesis to be answered during the defense:

1. Page 89: How did you determine the "hierarchical" transverse momentum (p_T) requirement on the lepton quadruplet (p_T > 20, 20, 10 and 7 GeV)?

2. Page 90: What is the low momentum cut on jet constituents that are entering the anti-kt jet reconstruction in your analysis? What does the acronym "AntiKt4EMTopo" mean?

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NUCLEAR PHYSICS INSTITUTE OF THE CAS, v. v. i.

250 68 ŘEŽ, CZECH REPUBLIC

3. Page 92: Can you please specify the purity of individual muon "types"?

4. Page 93: Can you be more specific and describe the Jet Vertex Tagger (JVT) used in your analysis? Unfortunately, the reference [162] is either incomplete or not accessible from outside of the ATLAS Collaboration.

5. Page 94: What determined your choice of the transverse parameter significance $d_0/\sigma(d_0)$ to be < 5 for electrons and < 3 for muons, respectively?

6. In the last sentence of your thesis you say that LHC Run3 statistics could potentially also enable polarization studies. Can you please describe the advantage/uniqueness of such studies?

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