Referee Report on the Doctoral Thesis

Author: **Kamil Skwarczyński**
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Title: **Constraining neutrino cross-section and flux models using T2K Near Detector with proton information in Markov chain Monte Carlo framework**

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Kamil Skwarczyński, as a member of the international T2K experiment, performed in his doctoral thesis a very detailed and comprehensive study of using T2K Near Detector to constrain neutrino cross-section and flux models in the neutrino oscillation analysis. This work is done within the Markov chain Monte Carlo framework and introduces new event samples splitting data based on protons and new systematic parameters describing neutrino cross-section. T2K is one of the world's key experiments studying this phenomenon of neutrino oscillations.

The thesis is divided into 8 chapters and 2 additional appendixes. The first chapter introduces the neutrino physics in rather detailed way, in general the neutrino oscillation and possible CP violation in the leptonic sector. Chapter 2 contains a description of the T2K experiment facilities, the Near and Far detectors with an emphasize on the ND280 detector which plays the crucial role in this work. Chapter 3 describes the ND280 analysis of the event samples and their composition, especially for the proton-tagged ones, used selection algorithms and binning. The sources of systematic uncertainties are outlined in Chapter 4. Here is for the first time visible own author's work with his implementation the systematic errors related to nucleons in final state interactions and 2p2h errors on ratio of pn to nn interactions. Chapter 5 is devoted to the T2K Oscillation analysis with two different approaches, frequentist and Bayesian, the latter in more details as the author's choice. Chapter 6 presents the fit results to both, ND280-only data and Near and Far detector joint data with many statistical and predictive methods and their validation approaches. In Chapter 7, the author presents his sensitivity study using proton kinematics variables in the fitting as a new approach for future T2K analysis, especially when the experiment anticipates the ongoing upgrade of the ND280 detector. Finally, Chapter 8 summarizes the results, compares them to other neutrino experiments as NOvA and SK experiments and discusses future analysis steps. In two appendixes are described many additional studies conducted by the author to help better understand the presented results, and shown plots for all samples and parameters.

Timeliness:
I think the submitted thesis is live and topical to the current situation in the particle experimental physics and in searching to solve issues of the nature as is the abundancy matter particles over antimatter ones in the universe and other fundamental questions. The oscillation phenomenon is the only effect which describes the physics beyond the Standard model of the elementary particles and forces and many parameters describing the neutrino oscillation are yet poorly known. And, within the T2K collaboration, the author's analysis is one of its highlights.

Methods and systematics:
The student shows in the entire thesis very good understanding complexity of such data analysis, how to deal it step by step. He understands basic physics behind the neutrino oscillation via study of available literature, understands how the experiment is to set up and what is its performance, how to use experimental data, validate different statistical approaches and make results from them, and finally how to conclude and summarize whole work. He was able to presents his and whole collaboration's work on international conferences.

Thesis goals:
I may say that the goals given to the student's study are very well mirrored and matched in his thesis, even I would say the results exceed the goals. This refers to chapter 7, even if it were not part of the dissertation, the analysis would still be complete and serve as a valuable work. In particular, the study of proton-tagged events using preliminary simulation of upgraded ND280 detector is extra work. Certainly, the results in the thesis are very useful within the T2K experiment collaboration. The student was chosen by the collaboration to present the work on the one of most important conference in the particle physics field, ICHEP 2022.

Scientific results and benefits:
Clearly, in the work there a lot of useful results, I will not comment on them. The presented results may be used not only in T2K experiment, but also by other experiments and to serve as a very reasonable starting point for other studies, especially when the experiment and beam facility undergo upgrades. One of beneficial studies might be the proposed joint analysis with the NOvA and SK experiments. And, the results provide a good basis for data analysis on a new successor HPK experiment.

I asset and recommend the submitted doctoral thesis hereby:
The Kamil Skwarczyński's work demonstrates author's assumptions to graduate with PhD degree.

The PhD thesis of Kamil Skwarczyński meets the criteria prescribed by the law for a doctoral dissertation. Therefore, I recommend that this dissertation be admitted to a public defense.

In Prague, May 11, 2023

Zálešák Jaroslav

RNDr. Jaroslav Zálešák, Ph.D.

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