The Doctoral Thesis Evaluation Report

Title	Measurement of the energy spectrum of cosmic rays using Cherenkov-dominated data at the Pierre Auger Observatory
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Study branch	Particle and Nuclear Physics

The doctoral thesis summarizes author's work on a novel analysis of the energy spectrum of very high energy cosmic rays measured at the Pierre Auger Observatory. It is well written and structured, and contributions of the author are clearly identifiable. The thesis demonstrate a solid understanding and knowledge of the research topic. Even if the list of references is complete and accurate, I would invite longer list of publications. A handful of typos and minor oversights (summarized in the appendix) do not lessen excellent quality of this work.

The author has been leading the development of the profile constrained geometry fit method and its application to Cherenkov-dominated extensive air showers measured by fluorescence telescopes. Author's contributions are manifold and include the trigger system study, the data reconstruction code, comprehensive Monte Carlo simulations, and evaluation of uncertainties and biases of the final cosmic ray energy spectrum, among others. Of particular importance are new portions of the official reconstruction code of the Pierre Auger Collaboration, which have been developed by the author during his doctoral study and can be used by any member of the Collaboration. The author has also investigated air shower events propagating with anomalous velocity, mass-dependent parameters of air showers with anomalous longitudinal profiles and described the muon production depth in the context of the Heitler-Matthews's model of extensive air showers. These studies are adequately described in the main text and technical implementation can be found in appendices.

Author's work materialized in a major enhancement of the capability of the fluorescence detector, which was designed to study fluorescence-dominated cosmic ray events and not Cherenkov-dominated ones. By including author's reconstruction of the latter events, the energy spectrum measured by a single self-calibrated experiment has been extended by more than one order of magnitude of energy in the comparison with preceding studies. Straightforward scientific outcomes of this new result are as follows: a cross-check of different reconstruction methods used by the Pierre Auger Collaboration; a comparison with spectra measured by other experiments operated at energies below the ankle region; a study of features of the cosmic ray flux over more than four orders of magnitude of energy, including the first measurement of so-called second knee by the Pierre Auger Observatory, which is invaluable for any study of cosmic ray sources and propagation. In summary, the thesis research generate significant new knowledge in the astroparticle physics field.

The presented work undoubtedly demonstrate author's ability to work independently and focus on a research task. The author has adequate understanding of the implications of his work in a broader scientific context.

In Chicago on Jun 10, 2020 Radomir Smida

Appendix

- Fig. 1.4, no energy of primary particles and zenith are given.
- p. 11: "...the second type measures evolution in one level of shower development only." Is this statement true also for highly inclined air showers sampled by water Cherenkov stations?
- p.14: "Each camera consists of 440 hexagonal phototubes", A reference to e.g. Fig. 2.7 would be handy here to give an idea about the layout of PMTs in the camera.
- p.14: Even if, the sampling (binning) time is given on p. 25, it would be good to have it in this section, because of its important for this work.
- p.15: The are of the Infill array is not given.
- p.19: "...at more than one FD site."
- Fig. 2.5: "...is taken from..."
- p.28: "tigger"
- Fig. 2.14 and 2.15 needs changes to be more readable
- p.41: "The EM contamination accounts for roughly 20% of the signal...". What is missing here, is a comment, how the EM-muon ratio changes with the zenith angle.
- Figure 2.19, Why the part between 1e15.5 and 1e16.3 is not shown?
- p.62: The detection efficiency is not defined, which makes it difficult to interpret values in Fig.3.17. In addition, how is handled a case when Eps_i equals to zero in Eq. (3.19)? And how are handled empty bins in the VA_{Xmax}-R_p space?
- Fig. 3.22: A box-plot is difficult to read. In addition, has the width of a box any meaning? Better way of presentation is shown in Fig. 3.23.
- Fig. 3.23, Why does the energy scale uncertainty decrease below 1e16 eV?
- p. 68: What is the exposure of the two time intervals used in the comparison?
- p. 70: "The normalization shifts are applied to the individual energy spectra to match the most likely overall normalization of the combined spectrum.", This sentence does not really explain, why and how is the normalization shift applied.

- Fig. 3.25: This combined energy spectrum is very important result and would benefit from having also residuals.

- Fig. 3.26: Is the normalization shift applied here?

- p. 72: "... Knee-like and Ankle-like features", More appropriate is hardening/ steepening and softening of the energy spectrum".

- p. 72: "the Cherenkov–domianted"

- p. 72 "These features are usually explained as a consequence of the rigidity, R, dependent acceleration in sources...", This is not the only explanation, because one can not exclude a rigidity-dependent escape of cosmic rays from the Galactic magnetic field.

- Fig. 3.27: If the KASCADE-Grande CR spectrum is included, why not the KASCADE one?

- p. 73: "Alternatively, the features at the highest energies can be interpreted by a pure proton spectrum favoured by the Telescope Array measurements. In this case, the Ankle dip at about 10^18.7 eV and the cut–off above 10^19.7 eV are caused by interactions of protons with the cosmic microwave background radiation, namely by the production of electron–positron pairs [75] and the photo–pion production [76, 77], respectively." This is incorrect, because the GZK flux suppression is present for any nucleus, not only protons.

- All energy spectrum figures should have at last two numbers on the y-axis.

- The term figure should be used instead of picture.