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Review of the doctoral dissertation of Mr. Iftikhar Ahmad entitled „Investigating backgrounds in dark matter searches: Argon-37 activation and cosmogenic neutron suppression in the DarkSide experiments"

The thesis concerns purity of argon to be used in an underground WIMP-like dark matter (DM) observatory DarkSide 20k (DS-20k), based on previous experience with DarkSide-50 (DS-50). The existence of dark matter, a mysterious massive substance of unknown nature which is much more widespread in the Universe than the matter we know, has been one of the most intriguing unsolved problems in physics for nearly a century. The available observational evidence pointing to dark matter comes from different domains of astrophysics and cosmology, and can hardly be disputed. Nevertheless, despite decades of dedicated observations and experiments, the nature of dark matter remains unknown. On the other hand, the increasing number of null results more and more constrain the ranges of properties of imaginable dark matter candidates which step by step brings us closer to solving the mystery. This work is an important contribution to one of such steps: DS-20k observatory dedicated to a direct search for still plausible particle candidates dubbed WIMP (Weakly Interacting Massive Particles). As the name says, these particles are expected to interact with the surrounding matter only weakly, to create very rare, though potentially still observable reactions. Given these expectations it is immediately clear that the volumes of the media to be used as a WIMP target must be large, and that the background signal must be understood to the deepest level. The thesis of Mr. Ahmad originally helps in such an understanding, addressing the issues related with using argon as the target medium in DS-20k.

The dissertation consists of 144 pages and is written in English. The layout is classical and logical. The first Chapter is devoted to presenting a comprehensive introduction to dark matter which is well readable and practically useful, especially for astrophysicists who do not specialize in dark matter, like the reviewer. In Chapter 2 the DarkSide experimental program is introduced, beginning from foundational physics concepts like DM-induced interactions in liquid argon, and then describing in detail technical aspects concerning DM signal discrimination and design of the detectors. Chapters 3, 4, and 5 contain a description of original work and the achievements of the candidate, with clear statements on the scope of his responsibilities, and with mentioning the collaborators wherever applicable (Chapter 4). The conclusion and outlook are given in Chapter 6.

The key achievements of the candidate presented in the dissertation and their impact on the field, mainly via the importance of the Dark Side experimental program, can be summarized as follows:

1. measuring activity induced by interactions of cosmic rays with argon during its transportation from the underground extraction and purification site to the location of the DS-50 observatory, and comparing it with the expected values calculated in another study (Ref. 150) - this result is crucial for validating the cosmic activation estimates for future experiments (Chapter 3);
2. performing advanced simulations which tell about the significance of WIMP-like events induced by cosmogenic muons in the planned DS-20k observatory, and concluding about the selection cuts needed to reduce the level of such a background to the minimum (Chapter 4);
3. making a significant contribution to hardware testing and development for DS-20k: active participation in testing of veto photon-detector units (vDPU) which have a critical importance for detecting photon signal coincidences of cosmogenic origin to veto the signal detected in the time projection chamber - the core part of the observatory, and thus reduce the background; performing data acquisition and analysis using the software tools provided by the collaboration, and writing own scripts useful for partial data analysis (Chapter 5).

The main concerns regarding the physics content of the thesis include:

Chapters 1 and 2: one topic which could have been mentioned in the context of physics objectives of the DarkSide program is lensing of hypothetical dark matter within the Solar System by massive bodies such as the Sun, plantes, and their moons. Some studies claim that DM overdensities due to such a lensing might reach even 7 orders of magnitude which would create unique observational opportunities such as short-term transient signal excesses, potentially important for the DS-20k science case.

Chapter 3: The estimation of the expected argon activity was performed by the candidate's collaborator John Vallivilayil Teena using his original software named COSAC described in the PhD thesis which is cited as Ref. 150. As it was clarified separately, Ref. 150 is not available publicly, and it contains neither a link to the source, nor the documentation of the mentioned software. There is also no reference to any peer reviewed article related to COSAC. In Section 4.3.1. of Ref. 150 the software framework of COSAC is described, but no information about the exact values of the steering parameters are given (subroutine `config`). In consequence, the scientific outcome of COSAC cannot be reproduced with the available information. In this situation it had to be stated clearly in the thesis of Mr. Ahmad that the status of the estimation result is preliminary, or unconfirmed, although promising in terms of consistency with the measurements. Moreover, the numbers concerning both the estimation by J. V. Teena, and the measurements of ^{37}Ar activity performed by Mr. Ahmad are presented inconsistently: 1) the estimation provided by J. V. Teena cited in Mr. Ahmad's thesis: 0.51 +0.11/-0.07 mBq/kg in the text (p. 62) vs. $>\sim 0.57 \pm \sim 0.12$ mBq/kg in Fig. 3.13 vs. the estimation in J. V. Teena's thesis: 0.47 +0.11/-0.1 mBq/kg (p. 62); 2) the measurement in Mr. Ahmad's thesis: 0.45 ± 0.039 mBq/kg in p. 62 (the text and Fig. 3.13 agree) vs. the measurement in J. V. Teena's thesis cited as Mr. Ahmad's work, p. 61: 0.28 ± 0.039; 3) date of comparison: 01-04-2015 in Mr. Ahmad's thesis (p. 62) vs. 10-04-2014 in J. V. Teena's thesis (p. 59). Especially the discrepancy in p. 2) draws an attention: the two values of activity are reported to be measured by Mr. Ahmad, and they differ by a factor of nearly 2. Moreover, the lower value is inconsistent with the estimation done with COSAC which is noted in J. V. Teena's thesis: "...both values ... differ significantly.". Such an inconsistency requires an explanation which seems to be missing in the thesis of Mr. Ahmad where the reader is

informed about "the agreement" without any additional comments, despite the numbers of Ref. 150 being cited and used. These apparent discrepancies together with the concerns about the software validation and reproducibility of its results significantly weaken the sounding of the conclusion (Section 3.6 where we read "The agreement ... supports..." and "This validation is important...").

Chapter 4.

- The outcome presented here seems to be highly dependent on the particle transport software used. The results of the thesis are obtained with FLUKA, but there are at least few other tools to simulate particle transport, e.g. SHIELD-HIT12A, MCNPX, or Geant4. Only the latter was mentioned once (p. 87), but with no reference (neither to the software documentation, nor to the cited simulations), and with no comment on whether it could be considered as an alternative tool with respect to FLUKA, or not. A discussion on pros and cons concerning a decision of using FLUKA is missing in the thesis, and it affects the conclusions regarding the effectiveness of the selections cuts that lead to the final result of the Chapter, namely limiting the cosmogenic neutron background to 0.1 neutron-induced recoils at 90% confidence level (p. 90). An example literature position where the differences between particle transport simulation software are discussed is [Eur. Phys. J. C70:543-553, 2010] where "areas with poor agreement" are identified in comparison between FLUKA and Geant4. One should also notice the technical weaknesses in FLUKA which are mentioned by Mr. Ahmad in p. 78: "in FLUKA simulation neither the charge transport nor the scintillation propagation is performed". Once such a weakness is pointed out, an immediate question arises on whether the other tools are better in this aspect or not, but we do not see an answer in the thesis. Given the above, the candidate should clearly admit that his result is only a partial contribution to the demanding task of determining efficient selection cuts, or explain why FLUKA is the only option. But even if the latter is the case, I would expect a discussion on the selection of configuration parameters to enable reproducibility of the results. It would also help better understand the uncertainties related to the models used, and their internal parameters, especially in cases where experimental data is absent and extrapolations are performed insead. The author notices the latter situation (top of p. 68) but he neither discusses nor comments the related uncertainties. It is of course a big task to study model-dependence of the selection cuts efficiency, but I understand that it is of a major importance for rare event observatories like DS-20k, so it should at least be mentioned in the conclusions. It would also help if all the simulation parameters are provided, e.g. in an appendix, otherwise other collaborators who would study model-dependence of the cuts might not find the result obtained by Mr. Ahmad useful.
- Another piece of discussion which I find to be missing in Chapter 4 is a possible impact of short-time transient excesses of the muon flux reaching the observation site on the expected number of cosmogenic WIMP-like events. The FLUKA simulations are performed for the "total muon flux", but is has not been discussed whether events like big extensive air showers, multi-core extensive air showers, air shower clusters, cosmic ray ensembles, or muon excesses due to transient space weather changes (e.g. ground level enhancements) could play a role (increase the uncertainty) of the final background level estimation using the proposed cuts. One could expect that there might be some effect: even if these transient excesses are rare and the assumed total muon flux is not affected within the investigated time window, a specific distribution of energies, arrival times, arrival directions and positions of incidence in the

imaginable groups of particles could in principle pose a challenge for the designed electronics and the adopted selection cuts, or if it doesn't, a relevant discussion would seem to be in place.

- In the context of the above doubts, the claimed "sufficiency" of the selection cuts for the rejection of all the neutron-induced backgrounds (pp. 90 and 118) for the investigated (large) exposure can be questioned, and thus this claim seems to be unjustified or premature. Another question is whether the exclusion of the background on the level of 0.1 events with 90% confidence level is sufficient for the ambitious s.

Chapter 5. I find it a very good idea and advantage of the PhD program undertaken by Mr. Ahmad that he had an opportunity to master his skills, and to contribute significantly to the field in at least three distinct research areas: data analysis (Chapter 3), simulations (Chapter 4), and hardware development and testing (Chapter 5) - such an extended and complete experience will no doubt help in his future career. One of significant achievements in Chapter 5 is no doubt developing original scripts which were used by other members of the DarkSide collaboration, as noted in p. 96. It is therefore a pity that these scripts were not exposed adequately in the thesis, or I was not able to find any further information on which scripts developed by the candidate were used in the collaboration. For sure no technical information like functional diagrams are provided. It is therefore impossible to assess the weight of this important achievement, although it does not significantly affect the overall assessment which is positive.

The other criticism is of minor importance and it concerns mainly the "reader satisfaction" aspects, including the overall elegance and the level of attention to details presented by the author. I will mention only examples of the issues which drew my attention, with the hope that these remarks will help Mr. Ahmad to write good articles in his future career:

- using jargon terms with no introduction (e.g. "neutrino fog" p. 37, "extracted electrons" p. 53);
- incomplete technical description of detectors (the depth underground is mentioned for the first time only in water equivalent meters, i.e. 3800 m w. e., in p. 37, and the reader learns only in p. 52 that it corresponds to the depth of 1400 meters);
- incomplete or meaningless sentences (in p. 27 "should achieve an exposure of 200 t × year and be able to detect DM" is meaningless without saying which DM parameter range would be in reach);
- not citing time scales (at least order of magnitude) for the introduced effects (pixel recovery time in p. 34; delayed and external cross-talks in p. 35);
- using acronyms or names without introducing (ARGO is mentioned as "the next step" in p. 27 without any reference, and introduced only later, in p. 46, it is also not listed in the List of Abbreviations);
- inconsistent conventions ("dark matter" vs. "Dark matter" in p. 3, "Auger electrons" vs. "auger electrons" in p. 50, dot or no dot at the end of a caption, e.g. Fig. 1.2 vs. Fig. 1.5.);
- not mentioning all the figures in the text (Fig. 3.13);
- confusing word mistakes ("higher"->"lower" in p. 61);
- confusing phrasing ("satellite projects (i.e. Urania and Aria [125])" in p. 41);
- missing units (muon flux in p. 66);
- misleading indices (CE_{NR}->CE_{ER} in p. 78);

- quite a few typos which should have been eliminated after a careful reading of own text by the author (e.g.: "s"->"S" caption Fig. 1.9; missing "Fig." before mentioning Fig 3.1 in p. 49; missing space in "figure4.2" in p. 68);
- checking the availability of the cited references (e.g. Ref. 150 available only for request).
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Weighing the above considerations, I have no doubts that the doctoral dissertation of Mr. Ahmad constitutes an original solution to a scientific problem, it demonstrates the candidate's general theoretical knowledge in astroparticle physics, and the candidate's ability to independently conduct scientific work.

Summing up, I consider the doctoral thesis of Mr. Iftikhar Ahmad to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.