Referee report on the PhD thesis of Monireh Kabinerzhad

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The PhD thesis describes an original work extending the single pion production models in neutrino interaction. The topic is of great interest for the present and future neutrino oscillation experiments, where neutrino cross sections are an important ingredient of the data analysis and of the estimation of systematic errors. The formulation described in this work allows to account for mass effects and for interference terms between resonant and non-resonant pion production, thus providing a self-consistent description of the one-pion production mechanism.

The thesis is well organized, clear, and well written. Improvements with respect to the Rein model are based on sound theoretical work. The candidate describes the formalism employed in deriving the cross sections in a clear way, demonstrating solid theoretical knowledge and the capability to apply this knowledge to a practical challenge and provide an original solution. The separation of theoretical derivation between the thesis itself and the appendix shows also the capability to judge and distinguish in between important topics containing new developments on one side, and technicalities on the other.

Extensive validation against the (unfortunately scarce) experimental data assess the validity of the formulation. At the same time, the candidate is able to underline and describe the impact of his original formulation by comparing with currently available models and with experimental data.

I greatly appreciated the effort made by the candidate in order to incorporate this theoretical work in a state-of-art Monte Carlo event generator, thus giving to this research a place in the worldwide effort towards better understanding of cross-section effects in neutrino oscillation experiments. This capability to go beyond the specificity of the topic and understand the broader scope of research is an important asset for the present and future activity of the PhD candidate.

The practical implementation in the NEUT code is very well documented, as well as the differences with respect to the model currently used in NEUT. A sound, scientific approach is adopted by the candidate, who first checks the technical correctness of the implementation, then proceeds with step-by-step model inter-comparisons, from single nucleons to nuclei, from single energies to complex spectra. Single-nucleon comparisons show improvements especially in the anti-neutrino sector, where the new model profits from the good theoretical

formulation as opposed to the need for parameter optimization in the standard NEUT models. Predictivity is obviously a per-SE advantage, especially when experimental data are scarce and/or carry large uncertainties. Applications to nuclear target and real experiments beautifully complement the theoretical work. Differences with respect to standard NEUT are described and interpreted with good insight, notwithstanding the fact that experimental uncertainties are sometimes larger than model discrepancies. Again, the good theoretical grounds of this new model represent a clear advantage with respect to other approaches.

In my opinion, this thesis is a very good work, original and complete. The candidate possess a very good theoretical background, follows a good methodology, has a clear vision of the worldwide state-of-art, and an uncommon, very welcome, attitude to the practical application of theoretical developments to experimental problems. The work presented here is surely useful for the whole neutrino community.

I have few comments/questions, and there are some spelling/typos or minor issues to be corrected:

Specific comments/questions

1. In chapters 1 and 2, and later in chapter 6, the author describes the implementation of neutrino scattering in the NEUT and GENIE Monte Carlo generators. The restriction to these two is arbitrary and, in my opinion, not justified. A precise description of NEUT is surely motivated by the forthcoming insertion of this new MK model in NEUT. However, other Monte Carlo generators exists besides NEUT and GENIE (Gibuu, Neugen..). Without giving a full description of all of them, the author should at least mention them and, to the best of his knowledge, explain what are the model used for one-pion production.

2. In section 2.1.1, and later on in the comparison with data, the interplay between resonance production and DIS is not well discussed. from the bottom paragraph in page 10 it seems that DIS is active in the W$<$ GeV region, but somehow tuned. The tuning is not clear, and the absence of one-pion production from DIS not clearly motivated. This issue should also be addressed when comparing to data: could it exist a one-pion "background" coming from DIS? If so, the model predictions at high neutrino energy will produce an overestimation of the observed one-pion cross-section.

3. Page 12, FERMI gas. I partially disagree. Of course a simplistic square-well FERMI gas is unrealistic, but there exist models with higher degree of sophistication (for instance local Fermi gas) that provide accurate description of the initial state.

4. 5.2.1 fitting M_A. maybe I do not understand, but I imagine that is this the same M_A entering in Quasi-Elastic scattering? If so, why is the value used here so different? If not, please explain (at least to me...)

5. fig 5.11 why are the theoretical prediction so different for the two I=3/2 reactions? I would expect them similar, and indeed the data points are similar, as well as the cross section values in ref 40. Is this a problem of normalization, or something else? please comment.

6. Fig 5.12, bottom plot. Maybe I am wrong, but this should be more or less the same as the bottom plot of fig 5.11, and indeed data points are. Why is the theoretical curve here a Δ like one?

7. Figures 5.20 and 5.21 . How are the curves normalized? here seems that there is a factor two difference in cross section in between the "Full model" and the RS model, that is not visible in figs 5.11 to 5.13. Please explain.

8. Figure 6.3 , reaction $\nu p \to \mu p \pi^+$, W distribution. The two distributions are slightly shifted, while all the previous comparisons between models (MK, RS, Rein, figures 5.11 and 5.23) seemed to show perfect agreement on the W distribution in this channel. Could the author please explain?

9. Section 7.1.4 The claim that figure 7.5 prefers the MK-model is to me not justified. Both models appear to be in agreement with data within experimental errors. Maybe the sentence can be weakened.

10. Section 7.2.1, total cross section: it would be more fair to say that the overall agreement is better with the NEUT-RS data (as from χ^2)

11. Minerνa anti-neutrino data. Here I find the re-scaling to event number completely inconsistent with the discussion about fig 5.15, where the higher cross section in MK was described as an improvement over RS. Rescaling means disclaiming this improvement.

12. page 137 bottom line *text* in the inequality

13. Fig 7.13 and discussion. Again, as for figure 7.5, no clear preference exists with respect to data, given also the large experimental errors.

14. section 7.3.1 Why is CH used as target instead of CH2?

15. chapter 7.4 The discrepancy in pion angular distribution is not so large in fig 7.13, and the agreement with data is similar for the two models. more generally, all comparisons presented in chapter 7 can only point to different predictions, not to better or worse agreement with data, just because data is not precise enough.

Minor issues, spelling and typographic errors

1. page 3, caption of table 1.1 *normal (inverted)* : add mass hierarchy

2. page 4 *rely on SPP model* relies

3. page 5 *the official neutrino Monte Carlo* official for T2K ? Maybe add the existence of other MCs?

4. page 9 the two sentences starting with *In resonant interaction* are not grammatically correct

5. chapter 2.1.3 FSI: pions can also scatter on nucleons without charge exchange, changing energy and direction

6. page 36 missing label after Equation 3.67. Same in page 46

7. page 40 last sentence *adopt* adapt

8. page 45 *carry a sing* carry a sign

9. page 69 sentence after eqn 4.110 , a spurious semicolon. Next sentence misses capital A

10. Figure 6.10 and text in 6.4.2 : specify that antineutrino are considered here.

11. section 7.2.2, figure 7.14 is never referenced in the text.

In my opinion the thesis satisfies the criteria and I recommend that it is admitted to the public defense.

Best Regards

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