PhD annual report

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Summary of research activity.

During the third year of PhD, I continued to work on the simulations of atmospheric muons for the KM3NeT experiment and compared the KM3NeT data with the simulation results.

As it was described in the first and second year reports, one the main goals of my work was to develop a framework to tune the MUPAGE parametrisation on the CORSIKA full Monte Carlo simulations.

In the last year of PhD, I have completed the tuning framework. In particular, new values of the MUPAGE parameters were obtained by fitting the muon distributions from the CORSIKA simulations using the most recent models available: Sibyll 2.3d for the high-energy hadronic interactions and the Global Spline Fit for the Cosmic Ray (CR) mass composition. The tuned MUPAGE agrees with CORSIKA within statistical fluctuation for both KM3NeT detectors. Therefore, it can be used as a faster alternative to the CORSIKA full MC simulation. The tuned MUPAGE results can be considered as the ones obtained with CORSIKA without the need to perform the full simulations.

Having the tuning framework completed, the next step of my analysis was to compare the simulation results with the data taken by the KM3NeT telescopes.

The first step in this comparison was to eliminate the pure background noise from the data, which includes the decays of ^{40}K and the bioluminescent light. That was done by applying the opportune selection criteria on the number of PhotoMultiplier Tube (PMT) hits (signals from PMTs that exceed the predefined threshold) and the value of reconstruction likelihood (goodness of the reconstruction).

The next step was to evaluate the capabilities to reconstruct the muon direction and energy with the KM3NeT detectors. The muon flux as a function of the cosine of the zenith angle, $\cos\theta$, is well reconstructed in the region $\cos\theta > 0.5$ for ORCA and $\cos\theta > 0.6$ for ARCA ($\cos\theta = 1$ means down-going muon). Evaluation of the energy reconstruction capabilities was also performed for both KM3NeT detectors. For the ORCA telescope, the true and reconstructed energy distributions start to agree for high-energy muons with $E > 10$ TeV, while for lower-energy particles the discrepancy is large. The ARCA evaluation results showed that the disagreement is substantial in the whole energy range. Hence, I decided to use only zenith distributions in the well-reconstructed $\cos\theta$ ranges for the final analysis.

Then, I estimated the systematic uncertainties. The uncertainties considered in this work include that on the CR flux, the light absorption length in seawater, the PMT quantum efficiency, and the high-energy hadronic interaction model. The CR flux uncertainties were estimated using the CORSIKA full MC simulation. All the other uncertainties mentioned were evaluated with the MUPAGE tuned on CORSIKA. To estimate the uncertainty on the water absorption length and PMT efficiency, $\pm10\%$ variations were assumed for both quantities. The uncertainty on the CR flux and its composition were evaluated using the data provided in the GSF model. The high-energy hadronic interaction uncertainties were estimated using the post-LHC models available in the MCEq software.

Finally, the KM3NeT data was compared to the MUPAGE tuned on CORSIKA including all the systematic uncertainties mentioned above. The comparison showed that the MC simulation underestimates the data for both KM3NeT detectors. The discrepancy goes beyond the uncertainties considered in this work. There are $\sim$40% more muons in the data with respect to the simulation. The lack of muons in the simulations with respect to the data is known for GeV muons, the so-called muon puzzle. The muon puzzle has been investigated using the data from the ground-based extensive air shower observatories. Muons that are detected by the KM3NeT telescopes have energies in the TeV range. Hence, the KM3NeT measurement that was performed in this work is complementary to the investigations of the muon puzzle which may provide new insights and the test-bench for the possible solutions.

Having the discrepancy between the KM3NeT data and simulation for the muon zenith distribution underwater, it is important to investigate if such discrepancy is also present for the sea level flux of TeV muons. This comparison was performed and it showed that the CORSIKA simulations with Sibyll 2.3d and GSF underestimate also the sea level muon flux at $\sim$30% level. That indirectly confirms that the KM3NeT simulation describes the muon propagation in water, the light generation, the detector response, and the muon reconstruction with a precision better than 10%. The 10% disagreement between the simulation and measurements at sea level and underwater may be explained by the uncertainties on the light absorption length in seawater and the detector response simulation.

List of conference presentations:

- 38th International Cosmic Ray Conference (ICRC 2023),
  Nagoya, Japan, July 26 - August 3 , 2023
  "Comparison of the atmospheric muon flux measured by the KM3NeT detectors with the CORSIKA simulation using the Global Spline Fit model" (the contribution was approved as a talk)

- 12th International Conference on New Frontiers in Physics (ICNFP 2023),
  Kolymbari, Crete, Greece, July 10 - July 23 , 2023
  "Latest results and outlook of the KM3NeT neutrino telescope" (the contribution was approved as a talk)

List of publications:

- ”First observation of the cosmic ray shadow of the Moon and the Sun with KM3NeT/ORCA”, S. Aiello et al., Eur. Phys. J. C **83**, 344 (2023)
- ”Comparison of the atmospheric muon flux measured by the KM3NeT detectors with the CORSIKA simulation using the Global Spline Fit model”, A. Romanov and P. Kalaczynski.
  To be published as the ICRC 2023 proceedings. The contribution was approved.
- ”Latest results and outlook of the KM3NeT neutrino telescope”, A. Romanov on behalf of the KM3NeT Collaboration.
  To be published as the ICNFP 2023 proceedings. The contribution was approved.