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Unveiling the seasonal variation of multi-muon events at the NOνA Detector

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Jordi Tuneu,[a,*] **Eva Santos**[a] **and Peter Filip**[a]

[a] *FZU - Institute of Physics of the Czech Academy of Sciences,*
Na Slovance 1, Prague, Czech Republic

E-mail: `tuneu@fzu.cz`, `esantos@fzu.cz`, `filip@fzu.cz`

In this contribution, we investigate the seasonal variation of multi-muon events observed by the NOνA Near Detector (ND) at Fermilab, using the general-purpose Monte Carlo code FLUKA-CERN to simulate the transport and interaction of the air-shower particles in the atmosphere and other media. Our atmospheric model uses air densities for winter and summer average profiles calculated from the temperature and geopotential information at 37 pressure levels given by the European Center for Medium-Range Weather Forecasts (ECMWF) datasets in situ. Our FLUKA geometry model also includes a layered underground approximated to match the NOνA ND and its location. We compare our simulation results with the measured seasonal flux modulation of multi-muon events by the NOνA ND. For the first time, we were able to describe the multi-muon excess in winter over summer quantitatively and its dependence on the multi-muon event multiplicity, as observed by NOνA. Finally, we compare our results for the muon flux at the surface and underground detector level obtained from FLUKA simulations with the previous work from other authors based on CORSIKA simulations. We try to understand the reasons for the discrepancy by nearly a factor of four between the results of two Monte Carlo codes.

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[*] Speaker

1. Introduction

Due to the yearly temperature excursion, the atmospheric profiles undergo seasonal variations that affect the height of the first interaction of cosmic rays, which results in a seasonal modulation of the secondary muon flux. The maximum amplitude of this modulation occurs between the winter and summer months. This effect was studied by the MINOS and NOνA Near Detectors (NDs) located 99 m underground at Fermilab [1, 2]. The MINOS cosmic data show that the total (single)-muon flux increases in summer and decreases in winter by ≈ 1% [3], and both experiments find the multi-muon event rates to reach a maximum during winter [1, 2]. The seasonal multi-muon flux oscillation magnitude is five times larger than that for *single*-muons, and it has an opposite phase. The MINOS Collaboration has proposed several mechanisms to explain the winter maximum for the observed multi-muon flux [3]. However, all of them fell short of describing the magnitude of the oscillation. A recent work [4] based on parameterizations derived from CORSIKA [5] simulations has also addressed this issue. Still, the predicted seasonal multi-muon oscillation magnitude (see [4], Figure 9) is four times smaller than in the MINOS and NOνA data. Understanding this problem could help improve existing Monte Carlo codes or hint at new physics in high-energy particle interactions.

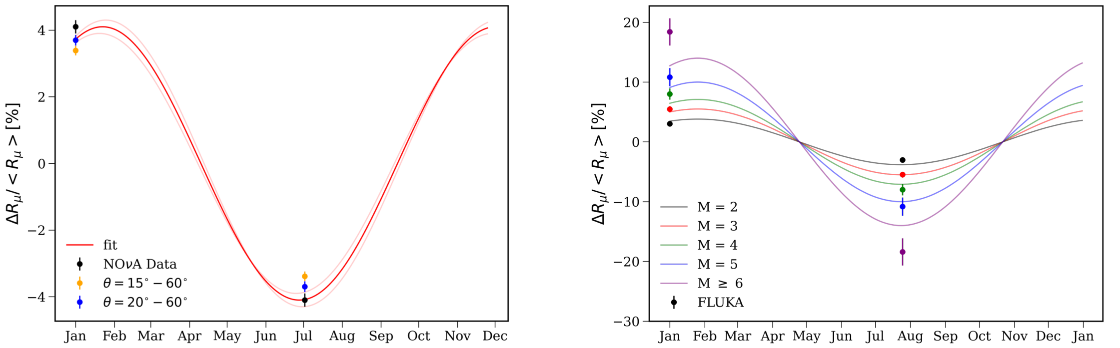
In this study, we use the Monte Carlo code FLUKA-CERN [6] to treat the transport and interaction of shower particles in several media. We used a 100-layered atmospheric model and several underground layers matching the properties of several media densities. We have calculated the average air densities of the summer and winter profiles from the ECMWF data [7] for 2017, the year of the NOνA ND data taking, at the NOνA/MINOS NDs location. The muon flux was analyzed at the surface (226 m above sea level) and at the detector plane (99 m underground) for the winter and summer atmospheric profiles. The description of the atmospheric model, the geometry layout, and the technical details of the FLUKA cosmic-ray shower library are described in [10].

2. Results

For our analysis, we have used the FLUKA-CERN shower library, generated as described in [9, 10], from which we extracted the muon momenta and the muon production coordinates.

2.1 Multi-muons: Seasonal Variation

To reduce the statistical uncertainties in the analysis of multi-muon events in each shower, we have implemented a grid of virtual NOνA ND detectors of size 16×4 m over a 4 km^2 area of the detector plane, located between $|x| < 1000$ m, $|y| < 1000$ m. Each shower is evaluated individually, from which we count the number of muons in each one of the 62500 virtual detectors. The resulting amplitude of the seasonal variation comes from the comparison of $\approx 1.35 \times 10^5$ and $\approx 1.16 \times 10^5$ cosmic-ray showers generated for each season within $15° < \theta < 60°$ and $20° < \theta < 60°$ zenith angle ranges. The multi-muon flux obtained for January and July 2017 is shown in Figure 1a. The two zenith-angle ranges, $\theta = 15° - 60°$ (orange), and $\theta = 20° - 60°$ (blue points), yield a seasonal amplitude of $V = 3.4\%$ and $V = 3.7\%$, respectively. The multi-muon multiplicity dependence obtained for the $\theta = 20° - 60°$ data sample is shown in Figure 1b, and it is found to agree with the fits to the NOνA data (colored lines).



(a) *Multi*-muon flux seasonal variation obtained with FLUKA for the zenith angle ranges $\theta = 20° - 60°$ (blue), and $\theta = 15° - 60°$ (orange). Two NOνA data points (black) and the cosine fit (red) are reproduced from NOνA data [1].

(b) *Multi*-muon flux seasonal variation obtained with FLUKA (colored points) for the multiplicities M = 2, 3, 4, 5 and ≥ 6 and the cosine fits (lines shown without fit uncertainties) obtained from the two years of NOνA data [1].

Figure 1: Seasonal variation for all multiplicities (left panel) and its multiplicity dependence (right panel).

2.2 CORSIKA-FLUKA comparison

The motivation to use FLUKA-CERN 4-2.2 [6] as the main Monte Carlo code for our analysis stemmed from the results of previous analyses in which the authors claimed not to be able to describe the NOνA/MINOS ND data when using CORSIKA or CORSIKA-based parametrizationss [2, 4].

Below, we try to understand the origin of this discrepancy by comparing our FLUKA results with the ones from CORSIKA 7.7500 [5]. For a fairer comparison between the two Monte Carlo codes, our CORSIKA simulations were produced as closely as possible to the ones from FLUKA (see [9]). We have compared 40000, 4000, and 1000 proton-induced showers with 10, 50, and 100 TeV primary energy, respectively, at the fixed zenith angles $\theta = 0°$, 30°, and 50°. For the CORSIKA simulations, we have used Sibyll 2.3d [12] as the high-energy hadronic interaction model to simulate hadronic interactions from the highest energies down to 80 GeV. Below 80 GeV, elastic and inelastic cross-sections of hadrons in air, particle production, and interactions are handled by FLUKA-INFN 2021.2.9 [13]. We used a 5-layered custom atmosphere fitted from the average winter and summer profiles used in our FLUKA simulations.

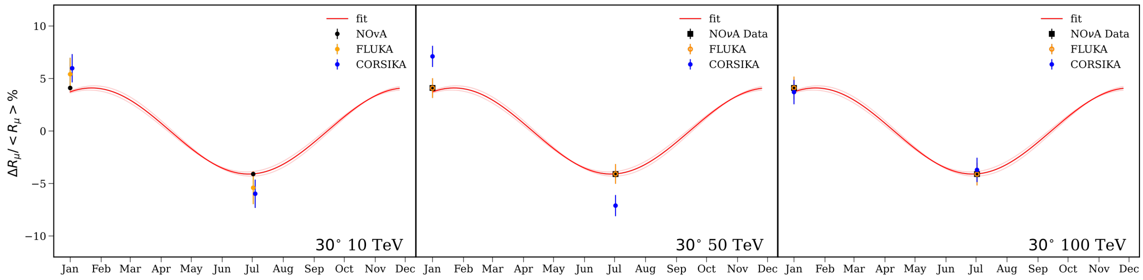


Figure 2: *Multi*-muon seasonal flux amplitude for CORSIKA (blue), and FLUKA (orange) 100, 50, and 10 TeV showers, $\theta = 30°$. The black square and the red line are (two years) NOνA data and the cosine fit.

While FLUKA can be used to simulate the particle transport from the top of the atmosphere down to the detector plane in several media, CORSIKA can only be used to simulate the shower development in the Earth's atmosphere. To compare the number of multi-muons at the underground detector plane, we consider the muons generated by both Monte Carlo codes at the (Fermilab) surface and apply the energy cut according to Elbert's equation [11] (avoiding this way any systematic differences between both Monte Carlo codes due to the transport of muons underground). We have applied energy cuts of 50 GeV for muons produced in showers with $\theta = 0°$, 55 GeV for $\theta = 30°$, and 75 GeV for $\theta = 50°$. The number of underground multi-muons was obtained by the same procedure (see section 2.1) for both Monte Carlo codes. From inspection of Figure 2, we conclude that both Monte Carlo codes predict a multi-muon seasonal modulation with a winter maximum and a summer minimum, consistent with the NOνA results. There is an excellent agreement between the FLUKA simulations and the NOνA data at 50 and 100 TeV. At 10 TeV, the FLUKA predictions are compatible with the NOνA results within 1σ statistical uncertainty.

On the other hand, we also observe a good agreement for FLUKA and CORSIKA simulations and NOνA for 10 and 100 TeV. Nonetheless, there is a slight tension between both Monte Carlo codes for 50 TeV. The reason for this behavior is still unknown, and further studies are being conducted.

Although the agreement between CORSIKA and FLUKA simulations is not perfect, we see that with CORSIKA, we can also predict a seasonal multi-muon variation with a phase consistent with the one observed by NOνA. Comparing to the results in [4], we outline the differences in the high- and low-energy hadronic interaction models, possibly different atmospheric profiles, and the simplified counting strategy, as the most plausible reasons for the discordant results. Namely, in [4], Sibyll 2.3c with UrQMD was used, whereas we opted for Sibyll 2.3d with FLUKA-INFN 2021.2.9. Our atmospheric profiles were taken from different database, and we have used the geopotential information. However, the most significant discrepancy between the two analyses may stem from the adopted multi-muon counting strategy in [4]. Finally, in [2], a much older CORSIKA version was used, and the few details provided do not allow us to draw a firm conclusion about those results.

3. Summary

Using a FLUKA-CERN shower library, we were able, for the first time, to reproduce the measured seasonal modulation and the amplitude of the multi-muon events observed at the NOνA and MINOS Near Detectors. We can also describe the phase and amplitude for higher multi-muon multiplicity classes. In a second step, we checked whether similar results could be reproduced with CORSIKA simulations conducted as closely as possible with our FLUKA library for a sample of proton-initiated showers with fixed energies and zenith angles. We conclude that CORSIKA can predict a seasonal multi-muon variation consistent with the NOνA results and FLUKA simulations, at 100 TeV. However, we observe discrepancies between CORSIKA and FLUKA at 50 TeV that still need to be addressed.

Acknowledgments

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References

[1] Acero, M. A. *et al.*, [NOνA Collaboration], Phys. Rev. D, **99**, 122004 (2019).

[2] Adamson, P. *et al.*, [MINOS Collaboration], Phys. Rev. D, **91**, 112006 (2015).

[3] Adamson P. *et al.*, [MINOS Collaboration], Phys. Rev. D **90**, 012010 (2014).

[4] Gaisser, T. K. and Verpoest, S., Astropart. Phys., **133**, 102630 (2021).

[5] Heck, D., Capdevielle, J., Schatz, J. N., Schatz, G. and Thouw, T. Report FZKA **6019** (1998).

[6] Battistoni, G. *et al.*, Annals Nucl. Energy **82**, 10-18 (2015).

[7] "European Centre for Medium-Range Weather Forecasts": `https://www.ecmwf.int/`

[8] Kling, A. *et al.*, Springer, Berlin, Heidelberg, (2001) 1033–1038.

[9] J. Tuneu, P. Filip, E. Santos EPJ Web Conf. **283** (2023), 05008.

[10] J. Tuneu, P. Filip, E. Santos PoS **ICRC2023** (2023), 347;
Gaisser, T., Riehn, F. and Stanev, T., PoS **ICRC2017** (2018), 533.

[11] J. W. Elbert, Proceedings of the DUMAND summer Workshop, La Jolla CA, USA (1979) 101–121;
J. W. Elbert, Proc. 16th ICRC 1979 Kyoto, Japan (1979), 405-409.

[12] F. Riehn, H. P. Dembinski, R. Engel, A. Fedynitch, T. K. Gaisser and T. Stanev, PoS **ICRC2017** (2018), 301; F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser and T. Stanev, Phys. Rev. D **102** (2020) no.6, 063002.

[13] "FLUKA": `http://www.fluka.org/fluka.php`