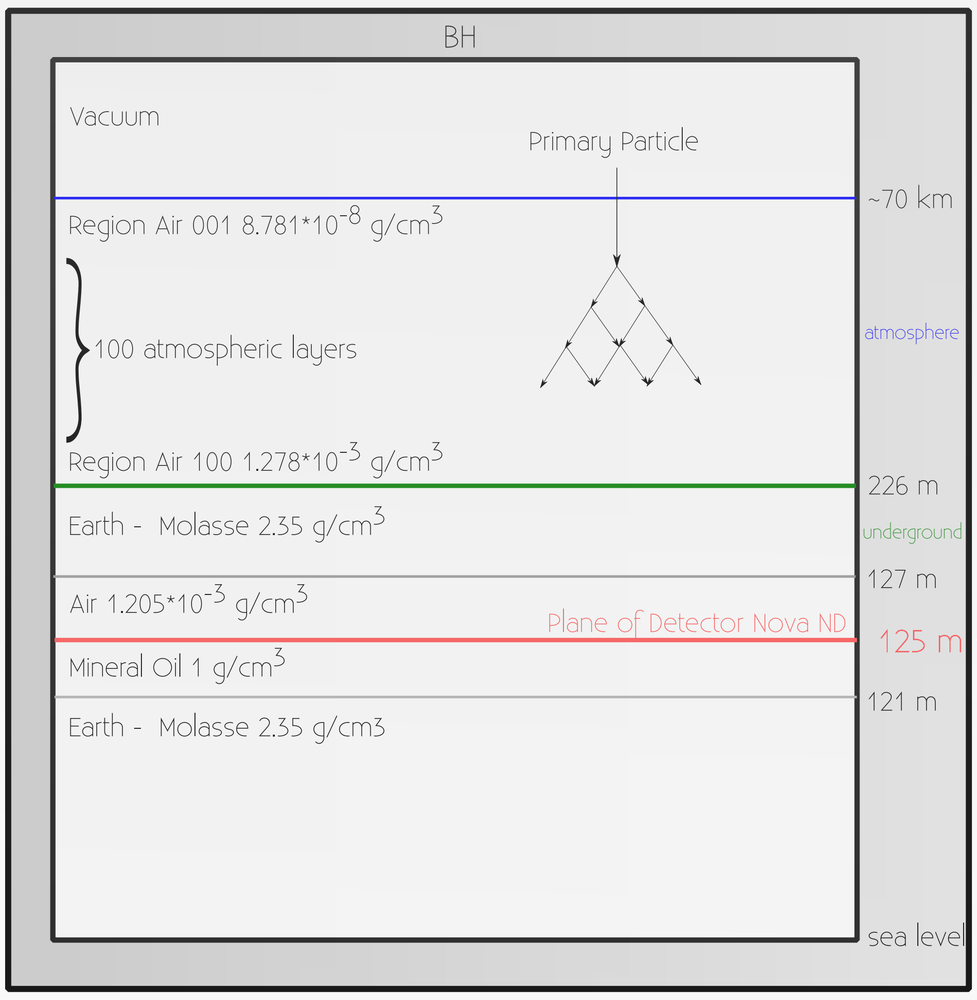
On the mystery of the multi-muon flux at the TeV cosmic-ray energy range

Jordi Tuneu[a] Eva Santos[a] Peter Filip[a]

[a]FZU - Institute of Physics of the Czech Academy od Sciences

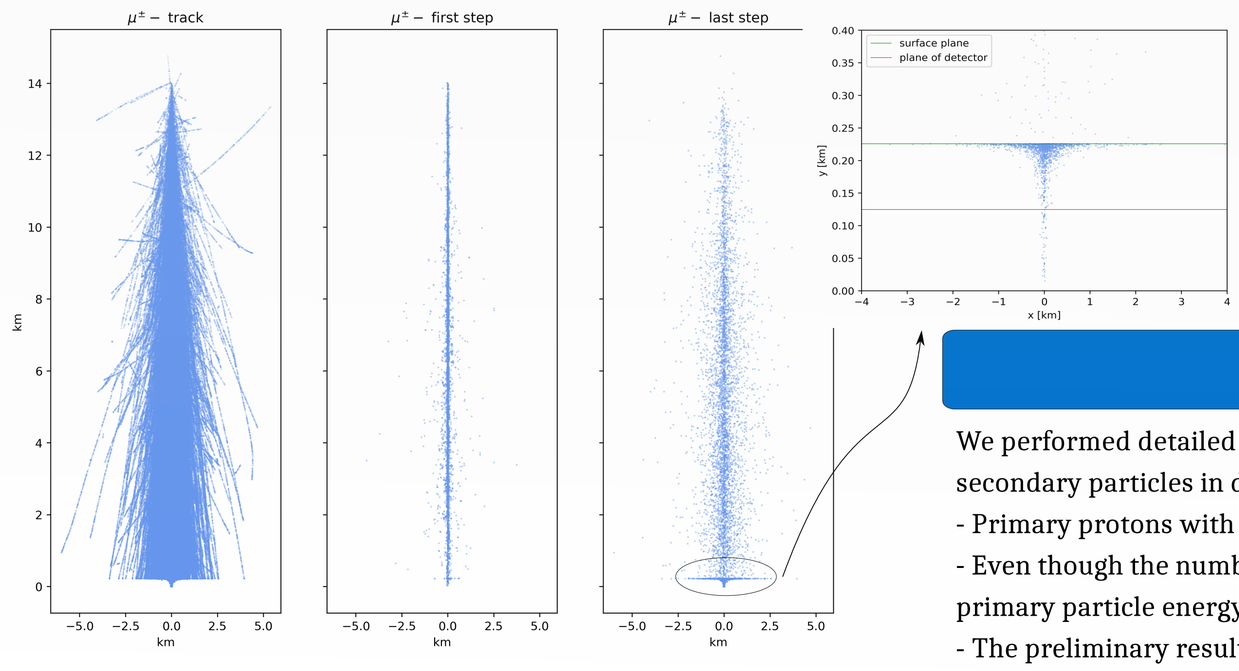
The muon component of air showers is not yet well described by actual Monte Carlo simulations. Many air shower experiments report discrepancies between data and Monte Carlo predictions, ranging from the TeV scale to the highest energies. One example we address is the seasonal variation of multiple-muon events observed by the NOvA Near Detector (ND). For our studies, we use the general-purpose Monte Carlo code Fluka to treat the transport and interactions of the shower particles in several media. Our design considers a multilayered atmosphere and a layered underground approximated to the NOvA Near Detector (ND) location and geometry. Our atmosphere model uses winter and summer air densities calculated from the temperatures and geopotential information for the pressure levels given by the European Center for Medium-Range Weather Forecasts (ECMWF) datasets in situ. Understanding the multi-muon flux at the High-Energy range may lead to a better description of Ultra-High-Energy muon production mechanisms in extensive air showers. In addition, it can help improving future Monte Carlo codes or hint at new physics processes or interactions.

FLUKA MODEL



We use the 100 atmospheric layers Monte Carlo model from Fluka Cern 4-2.2 [1] and adapt it for the NOvA ND geometry and location taking into account atmospheric densities profiles for winter and summer and extending layers underground for transport and interaction calculation of the particles.

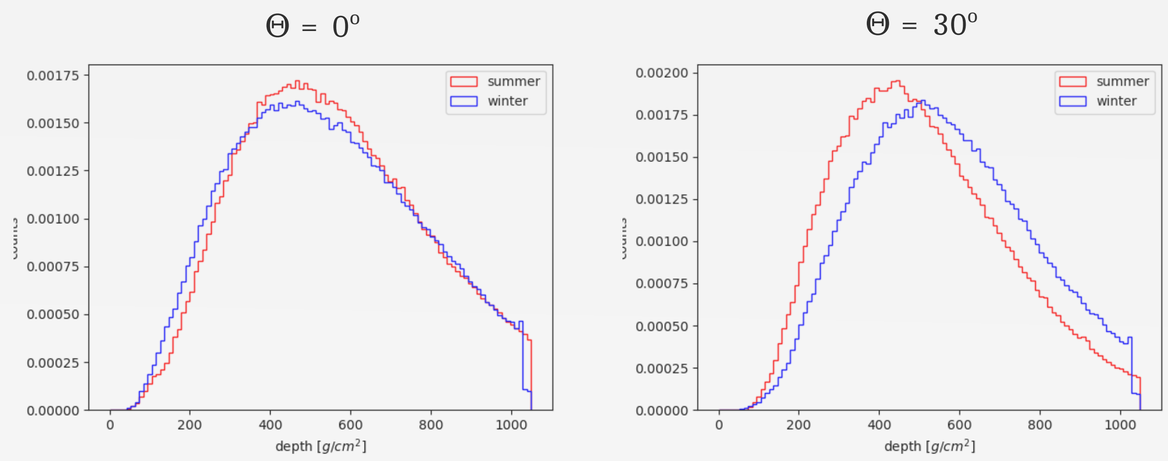
DATA



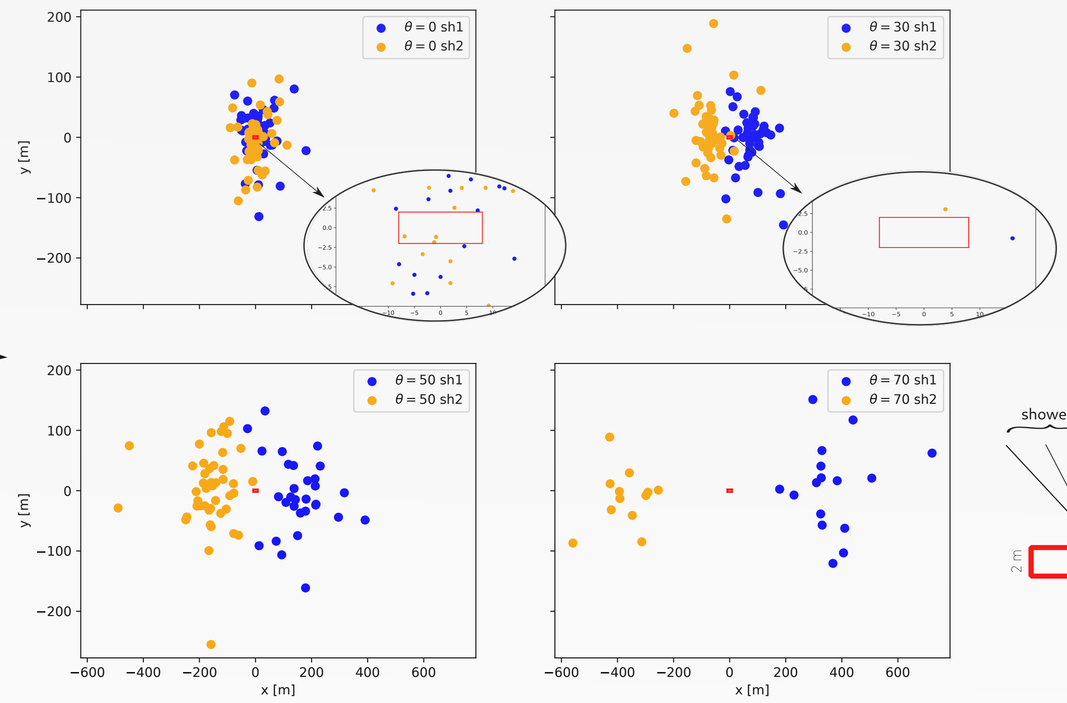
From the FLUKA outputs, we obtain, at each step, the kinetic energy, number of interactions, position, momentum, and director cosines for kaons, pions, muons, and their ancestors. After processing the output files, we filter the data to extract the first and last steps of the particle of interest. For showers above 100 TeV, we don't record all the tracks due to the file size.

PRELIMINARY RESULTS

Atmospheric profiles for summer and winter



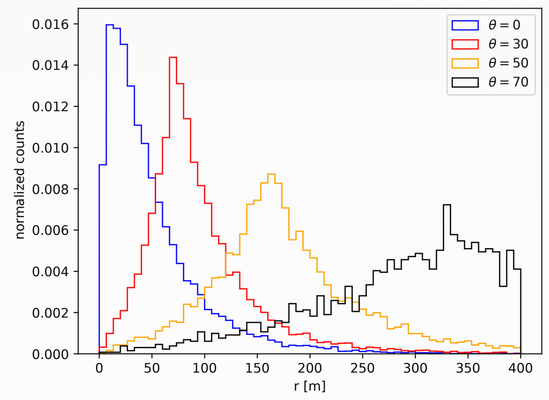
Muons at plane of the detector



Number of muons at the plane detector for different Θ from a 100 TeV primary proton.

Θ	summer	winter	σ_x(m)	σ_y(m)	σ_r(m)
0	50.46	49.96	52.65	54.21	54.62
30	44.54	44.27	63.66	59.17	60.30
50	32.8	32.78	97.33	76.20	89.58
70	17.62	17.15	235.50	152.09	194.79

Probability of detection as a function of r from the detector core



CONCLUSIONS

We performed detailed atmospheric Monte Carlo simulations to treat the transport and interactions of primary and secondary particles in different media:

- Primary protons with different zenith angles show different profiles for winter and summer atmospheres modeled.
- Even though the number of muons passing through the detector plane is similar in winter and summer. Other factors like primary particle energy, zenith angle, and radial distance of the impact seem relevant to answer the work from [2].
- The preliminary results are from 100 TeV proton-initiated shower simulations. The complete dataset comprises more energetic showers up to 100 PeV involving randomized azimuth angles in a 360-degree range and other primary particle species. Full production is now running.
- This work may hint at problems in Monte Carlo simulation codes describing the multi-muon flux at several underground detectors.

ACKNOWLEDGMENTS

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REFERENCES

> [1] Battistoni, Giuseppe, et al. "Overview of the FLUKA code." Annals of Nuclear Energy 82 (2015).
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> [3] Acero, Mario A., et al. "Seasonal variation of multiple-muon cosmic ray air showers observed in the NOvA detector on the surface." Physical Review D 104.1 (2021): 012014.