TAUP VIENNA 2023

FZU Institute of Physics of the Czech Academy of Sciences

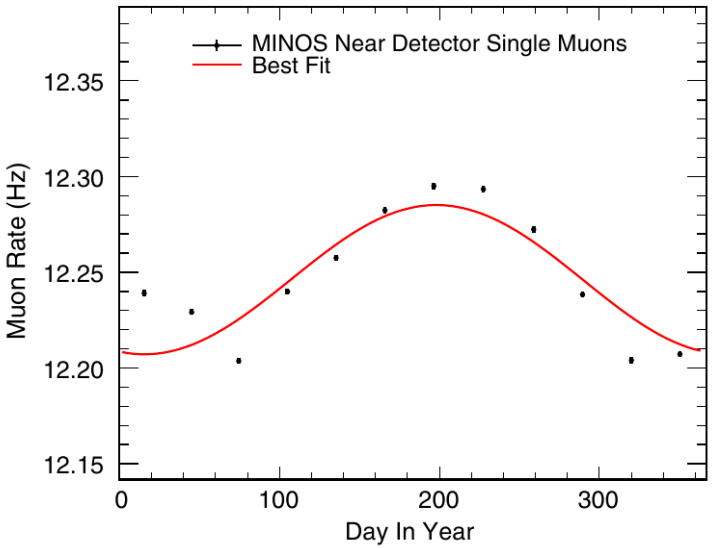
Unveiling the seasonal variation of multi-muon events at the NOvA Near Detector

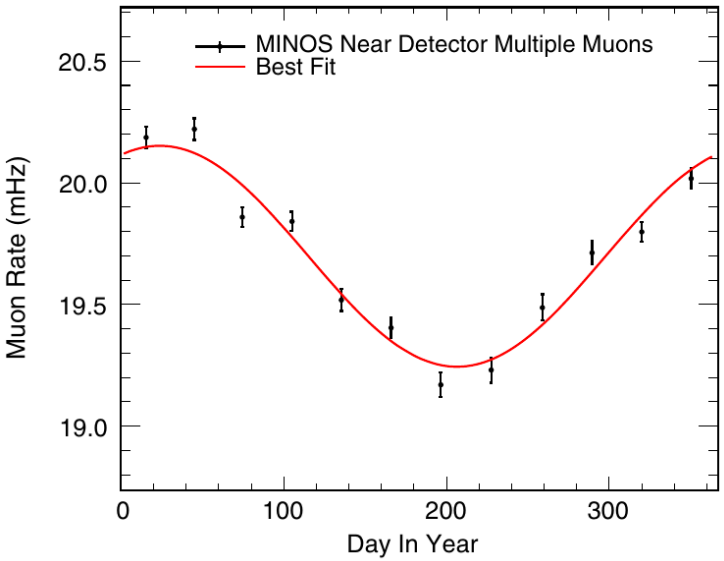
Jordi Tuneu[a] Eva Santos[a] Peter Filip[a]
[a]FZU - Institute of Physics of the Czech Academy of Sciences

> MOTIVATION

> Unexpected Seasonal Variation

MINOS Data PHYSICAL REVIEW D **91,** 112006 (2015)





"Observation of seasonal variation of atmospheric multiple-muon events in the MINOS Near and Far Detectors." 2015

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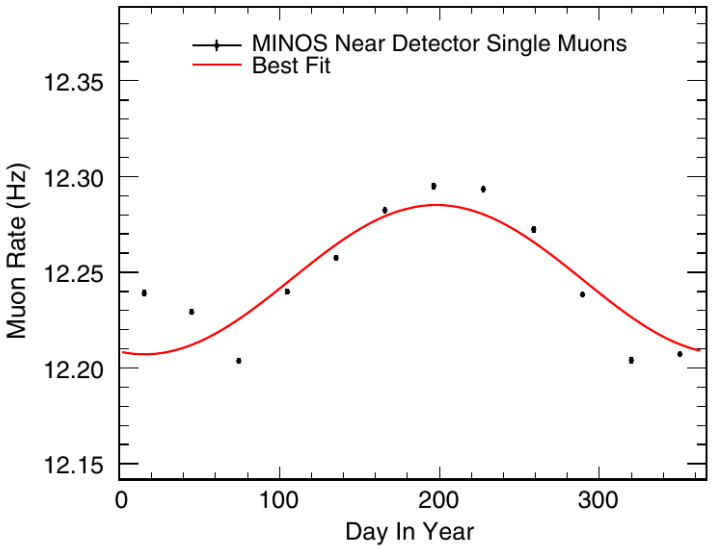
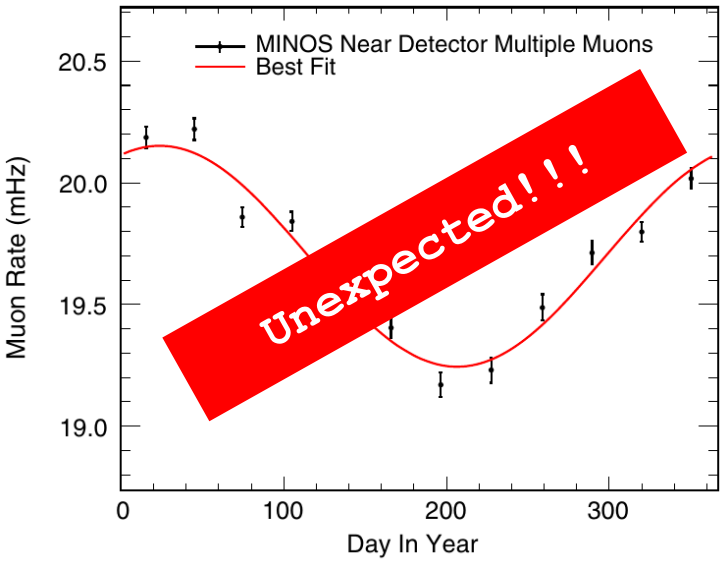
MINOS Data





"Observation of seasonal variation of atmospheric multiple-muon events in the MINOS Near and Far Detectors." 2015

> MOTIVATION

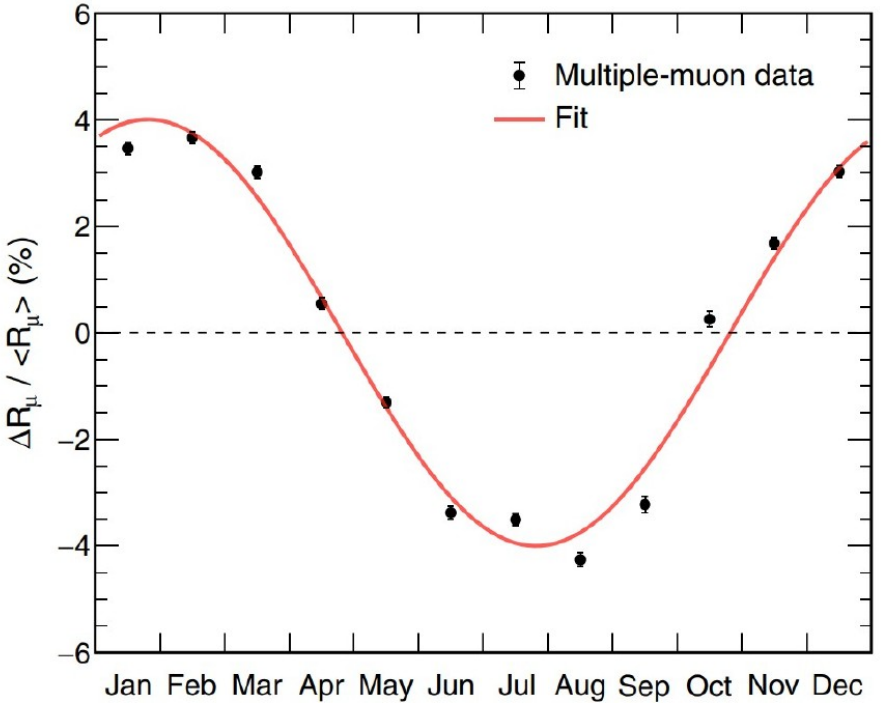
> Unexpected Seasonal Variation

> Opposite Seasonal Variation for multi-muon events.

> Around 4% difference.

> Simulations **have not** reproduced correctly the multi-muon Seasonal Variation.

Multimuon NOνA Data

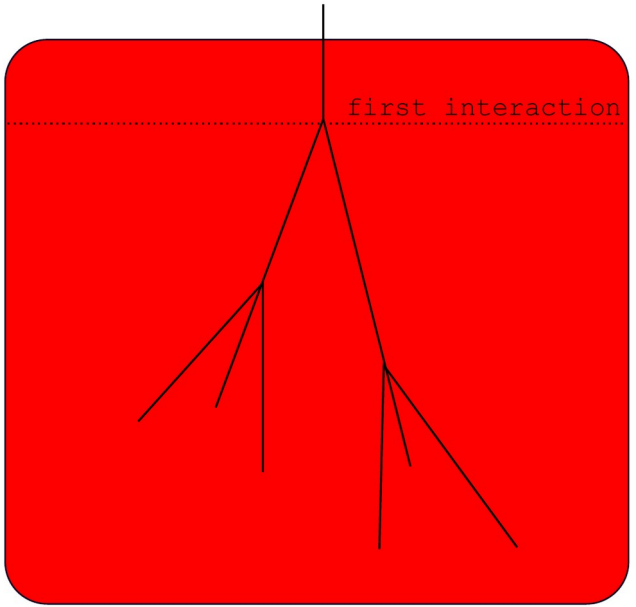


Percentage rate variation of multiple muons in the NOνA ND as a function of month of the year.

> MOTIVATION

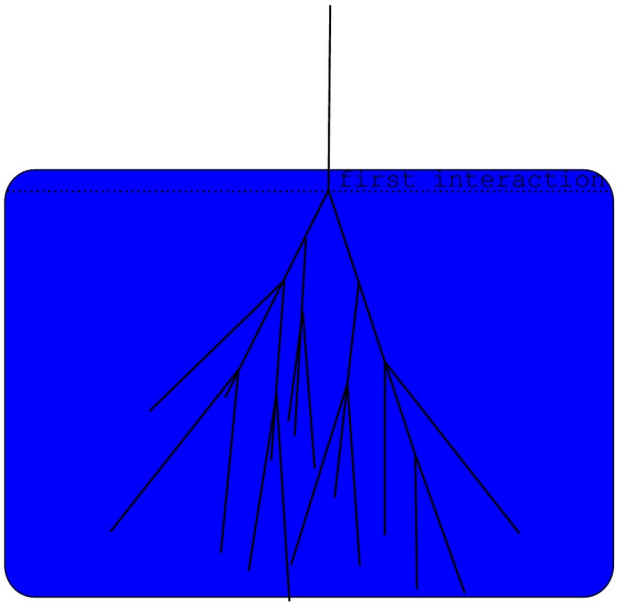
μ energy of interest above 50 GeV

summer



Less interactions
More decays π -> μ

winter



More interactions
Less decays π -> μ

Expected more μ in summer than in winter (< 1%)

> GEOMETRY

> FLUKA SIMULATION

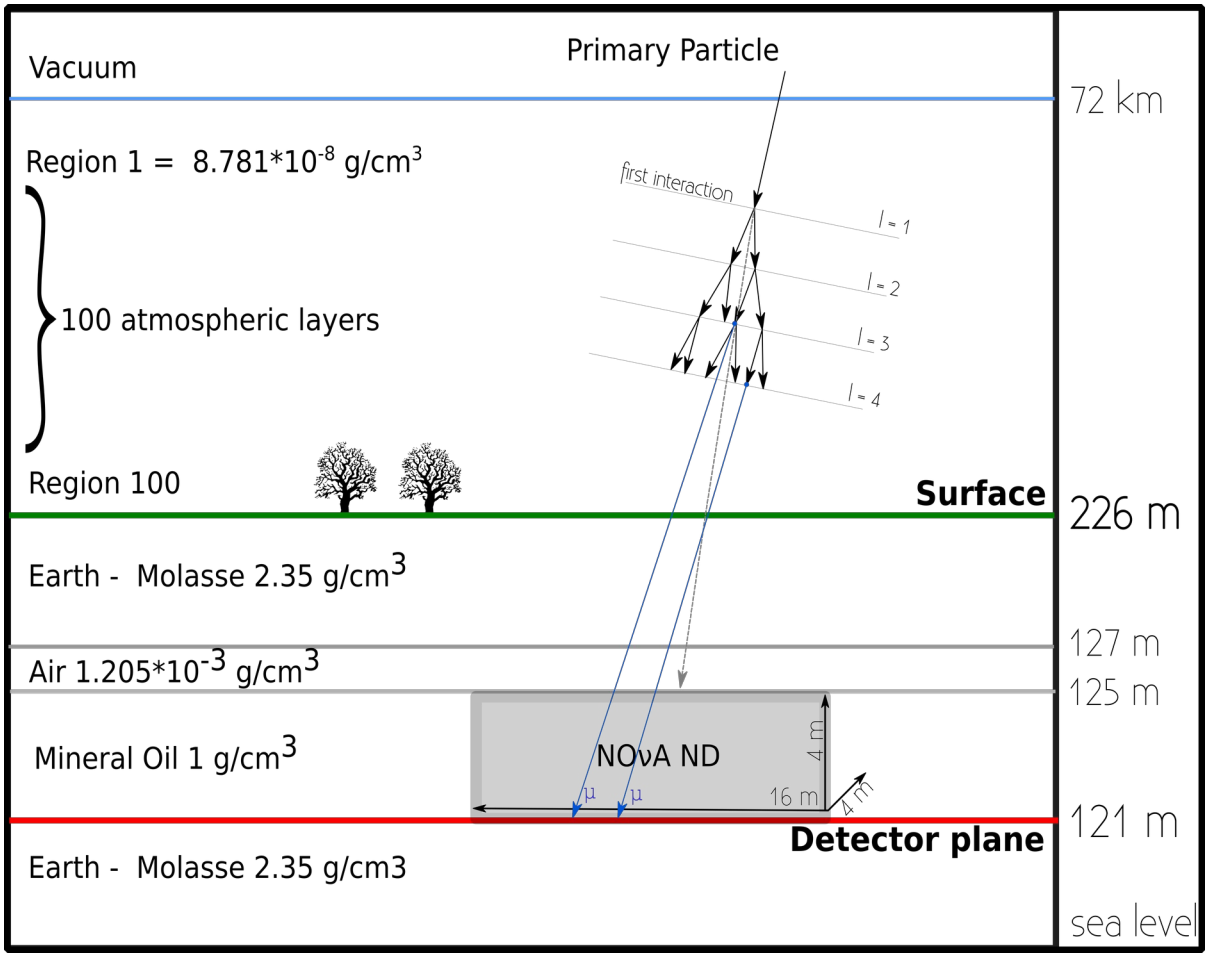
> FLUKA-CERN-4.2.3

> Averaged atmospheres of JAN and JUL 2017

> Data calculated from the temperature and geopotential at 37 pressures level from **European Center for Medium-Range Weather Forecasts (ECMWF).**

> 100 atmospheric layers

> Transport underground



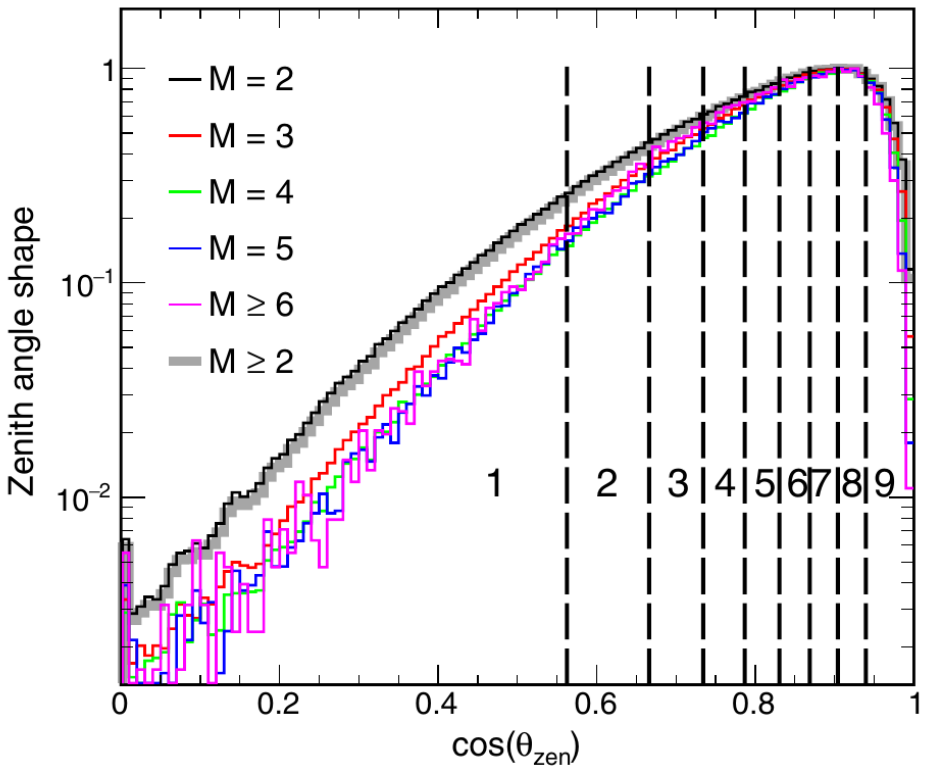
> MONTE CARLO SHOWER LIBRARY (SAMPLE)

> ~120,000 showers.

> To reproduce NOvA detector zenith angle acceptance:

Angle distribution from
θ = 20° to θ = 60°

Multimuons data from NOvA ND



Zenith angle distribution in a multiple-muon event in the NOνA ND.
"Observation of seasonal variation of atmospheric multiple-muon events in the NOvA Near Detector." 2019

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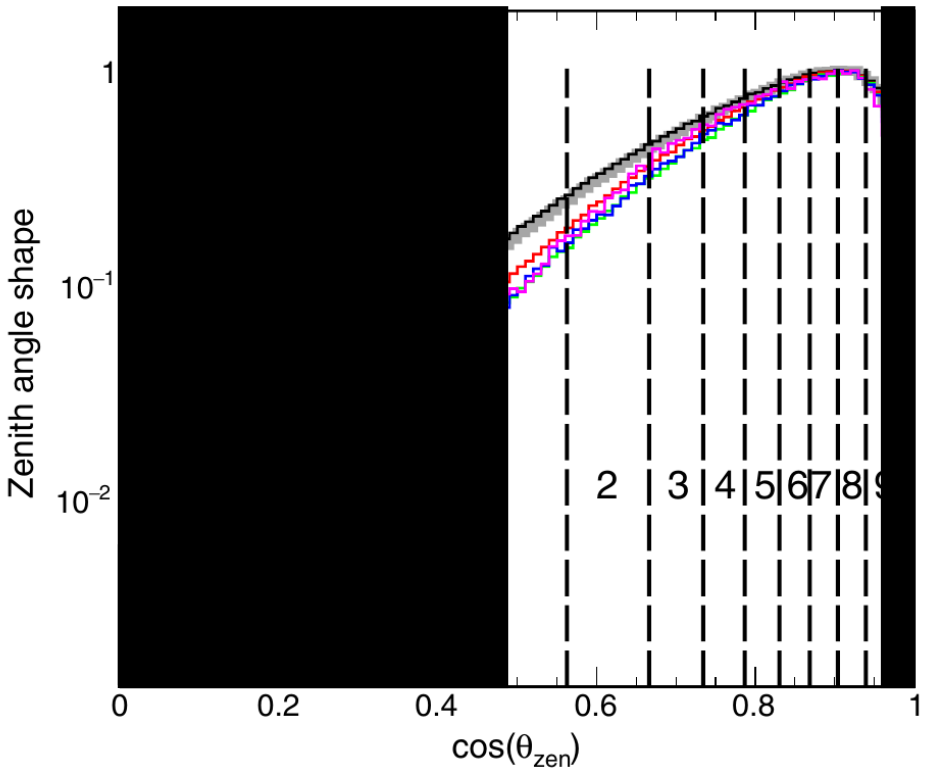

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Power-law from 10 TeV to 1 PeV
(γ=2.7)

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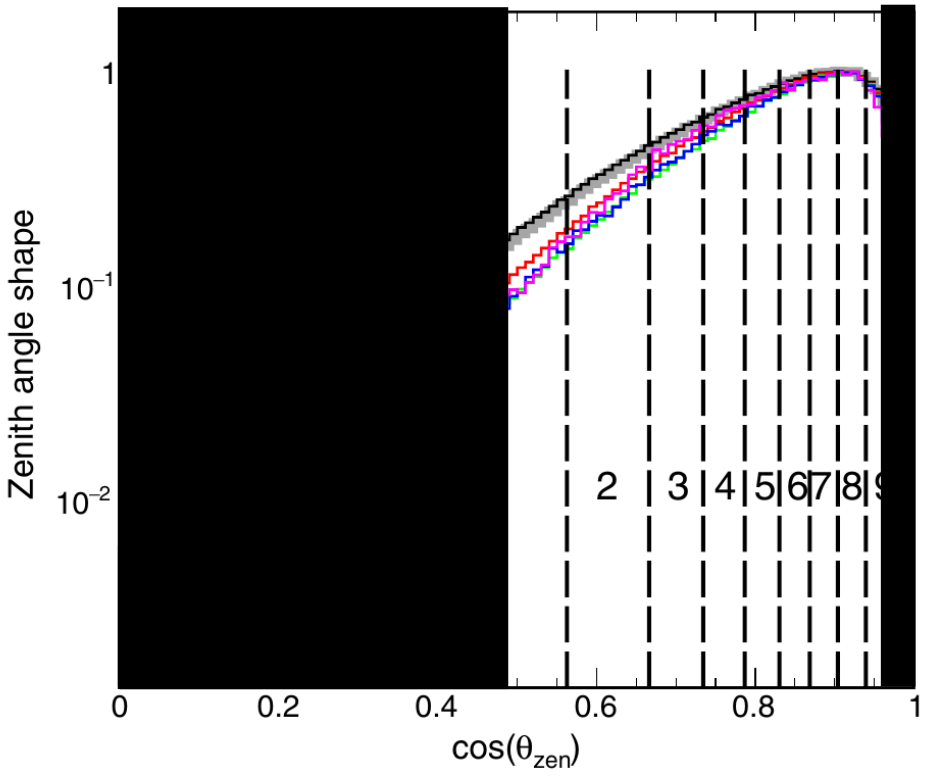

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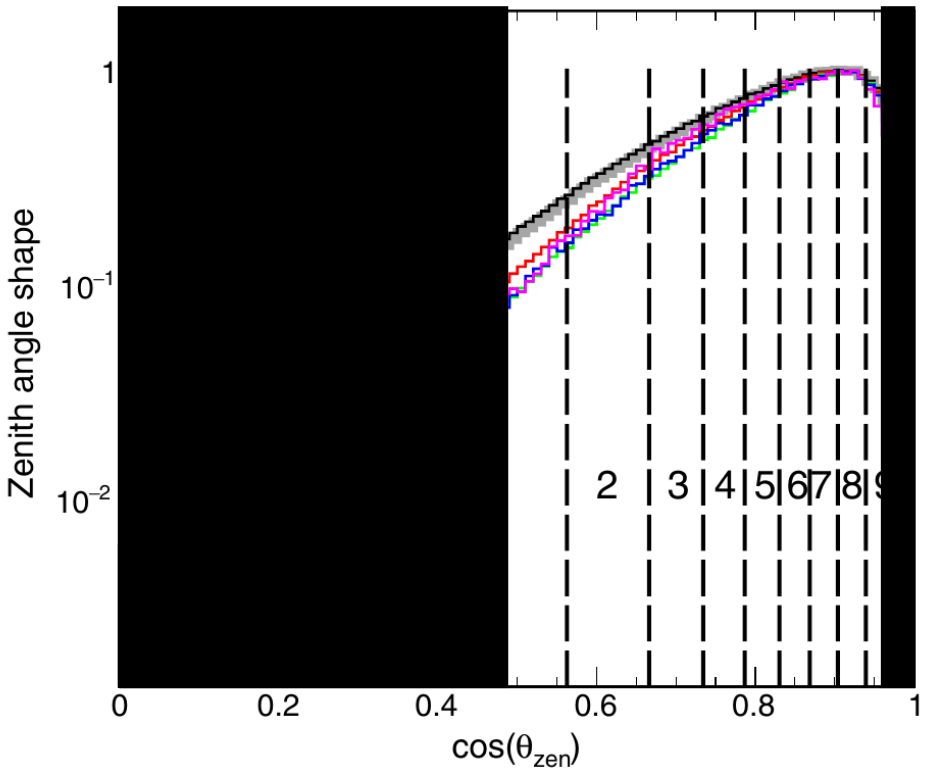
Power-law from 10 TeV to 1 PeV
(γ=2.7)

> Ratio Species Global Spline Fit (GSF) model:

P	He	N	Fe
1	1	0.43	0.23

Multimuons data from NOvA ND



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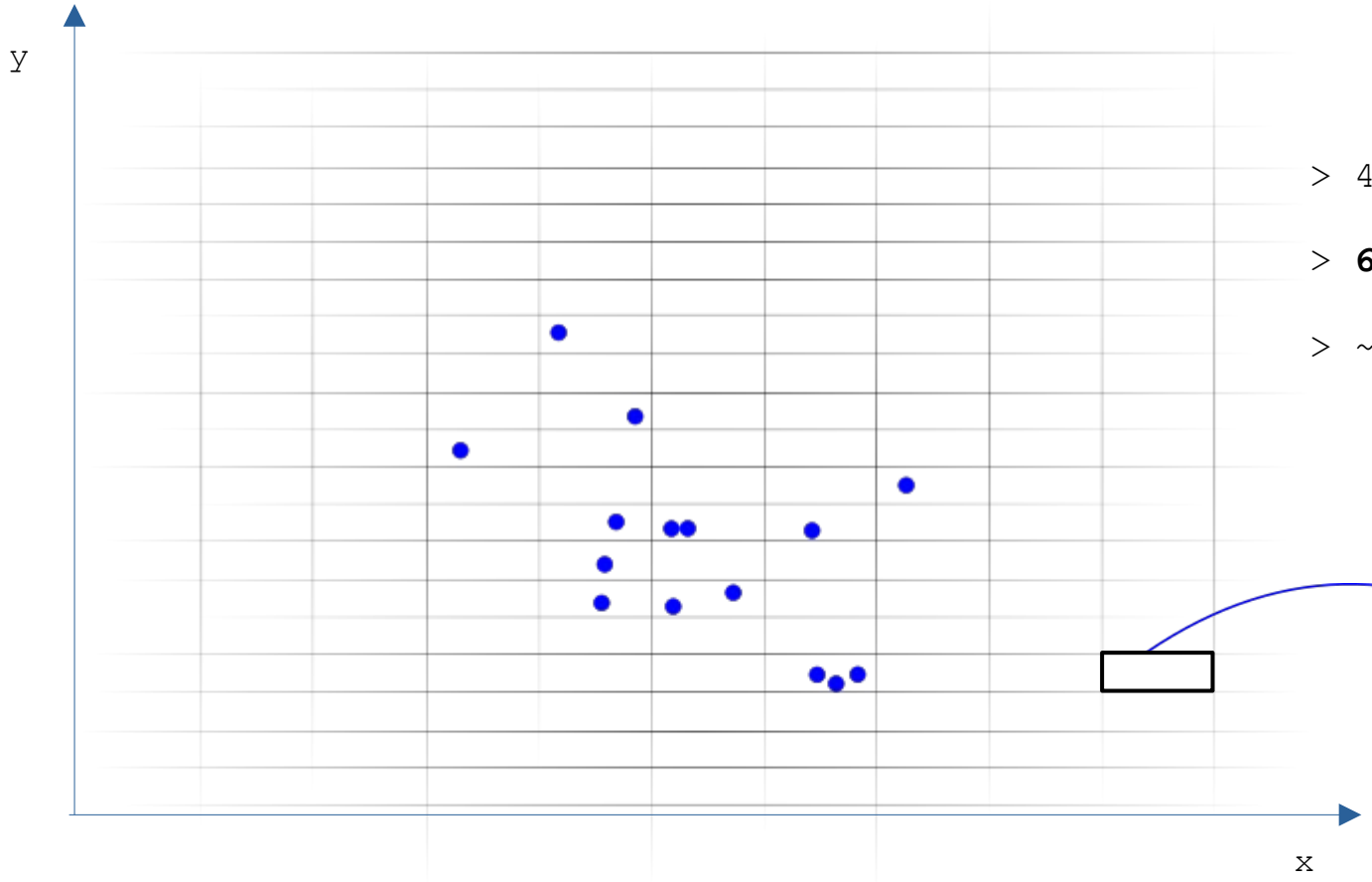
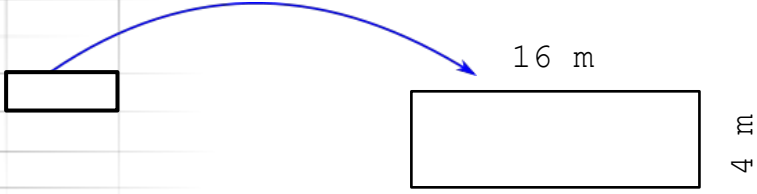
> MULTIMUON SPOTTER



> 4 km^2 Area

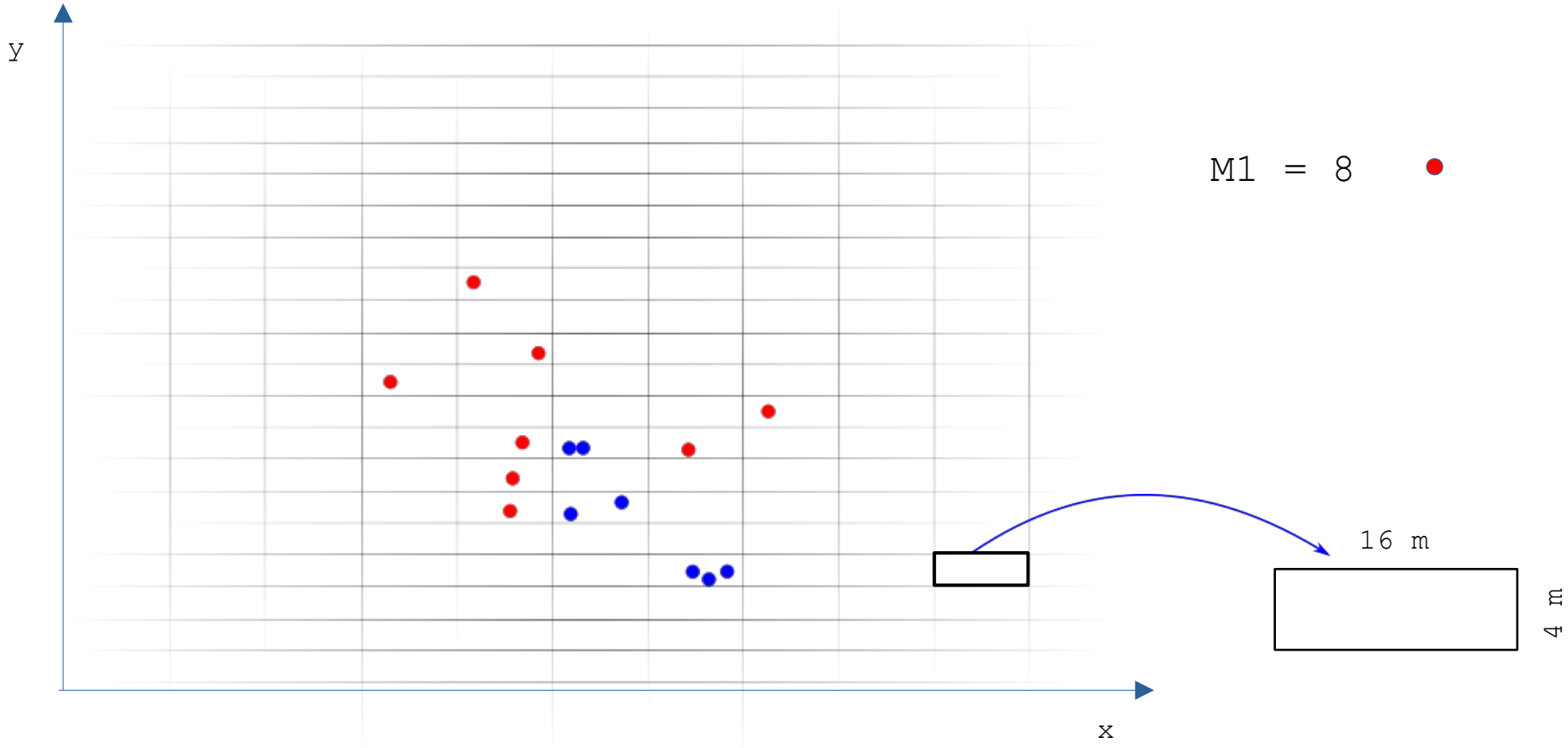
> **62500** *Virtual* detectors

> ~120x10^3 showers.



Detector plane at 121 m a.s.l
at **100 m underground**

> MULTIMUON SPOTTER



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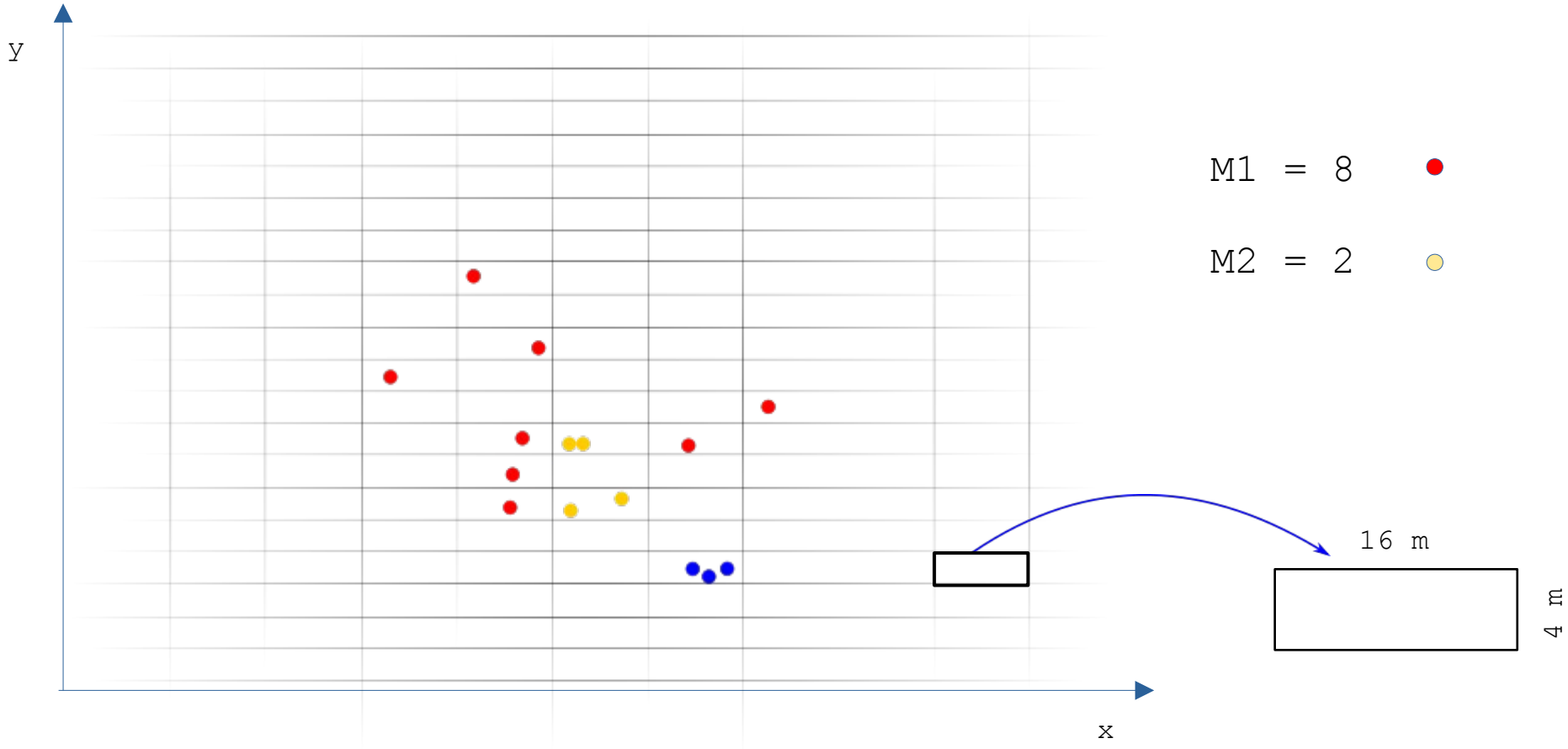

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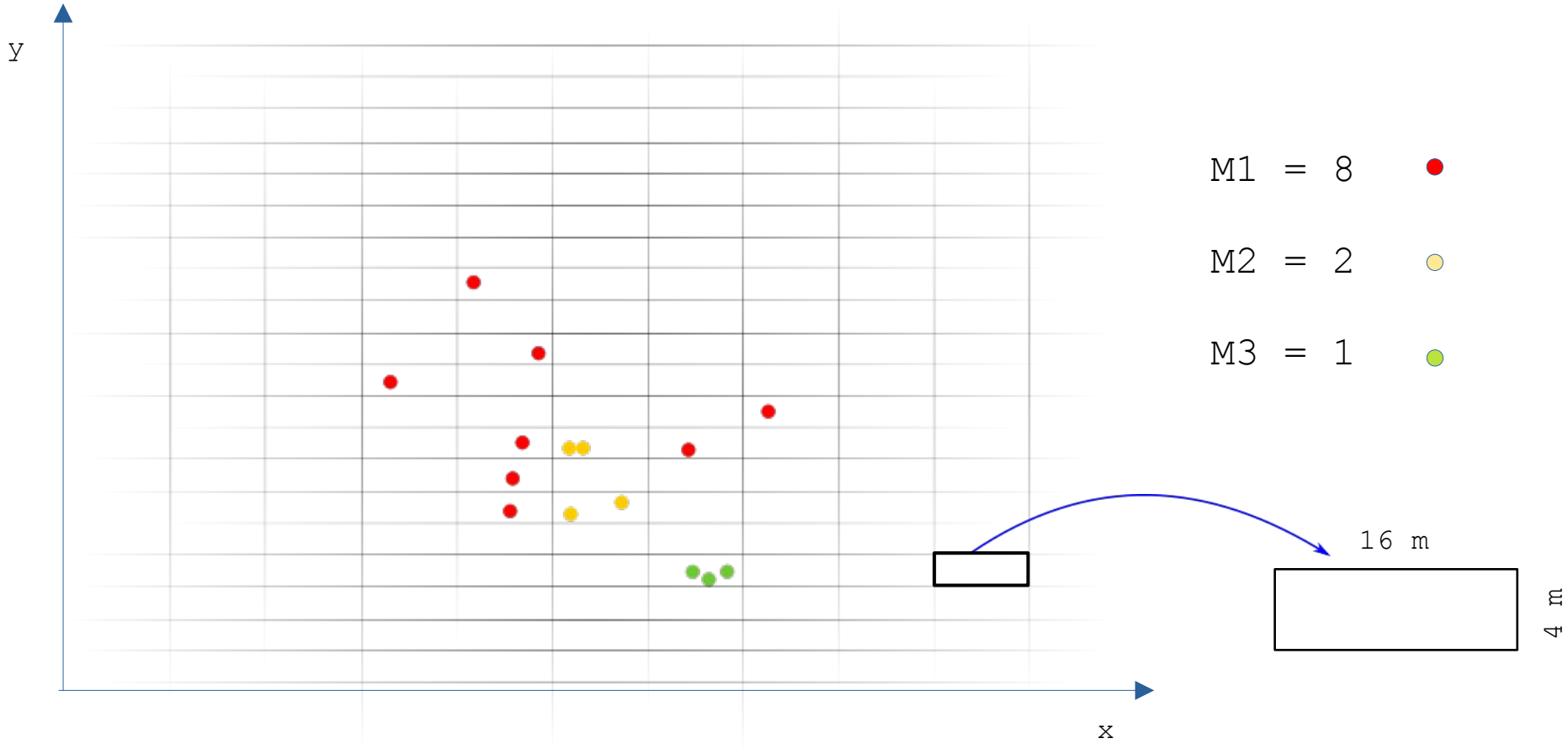

Detector plane at 121 m a.s.l
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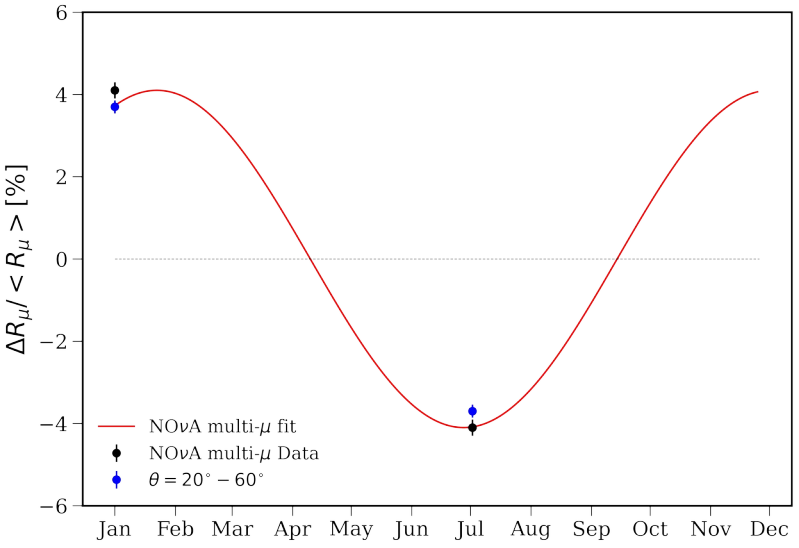
> FLUKA SIMULATION RESULTS

> Multiplicity ≥ 2

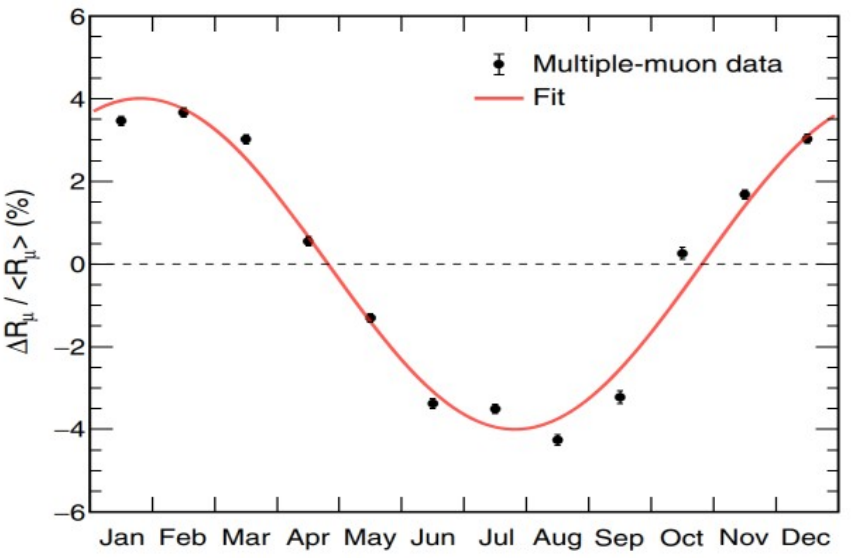
FLUKA Simulations

Multiplicity ≥ 2



NOνA data

Multiplicity ≥ 2



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FLUKA Simulations

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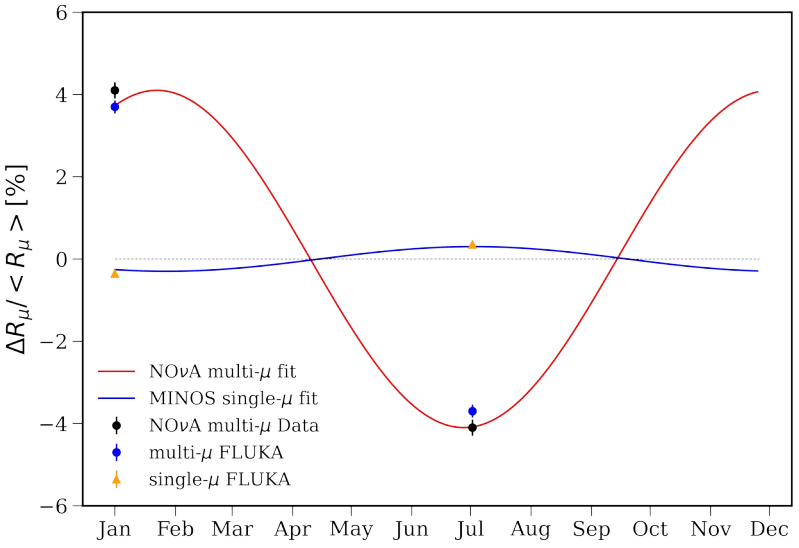
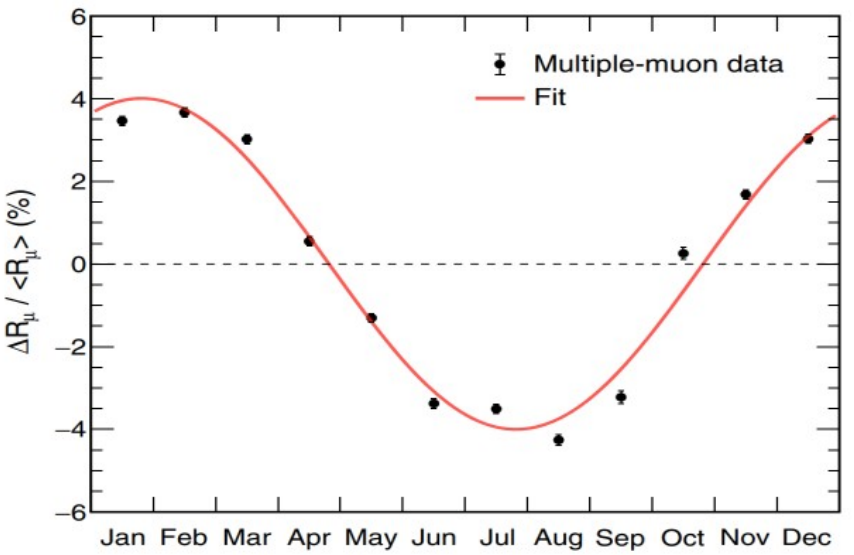


NOνA data

Multiplicity ≥ 2

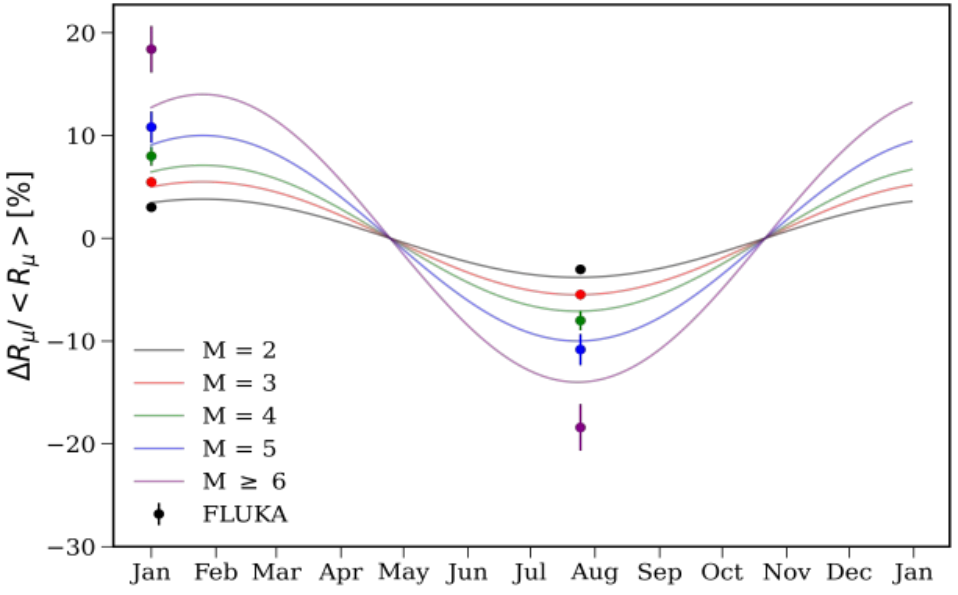


> FLUKA SIMULATIONS RESULTS

> Multiplicity Dependence of Seasonal Variation

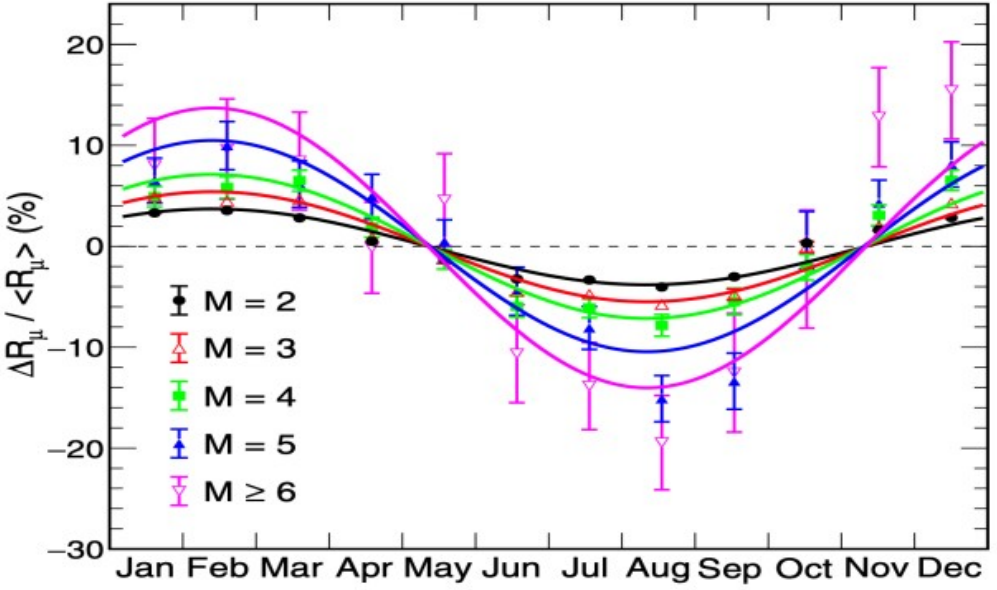
FLUKA Simulations

Multiplicities M = 2, 3, 4, 5, ≥ 6



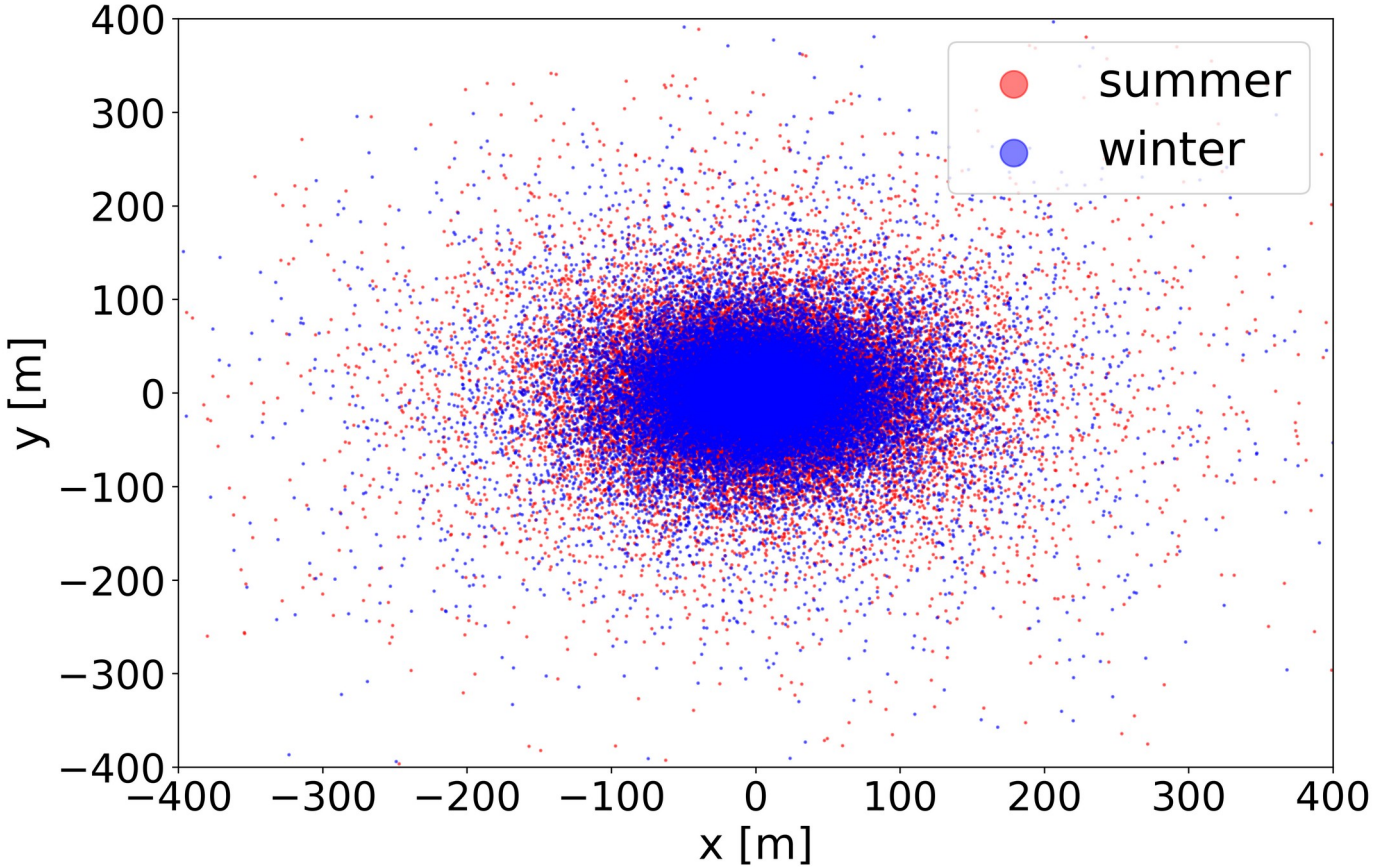
NOvA data

Multiplicities M = 2, 3, 4, 5, ≥ 6



> BACKUP SLIDES

> Spatial Distribution



FLUKA simulation. Muons from 1000 showers at the detector plane.

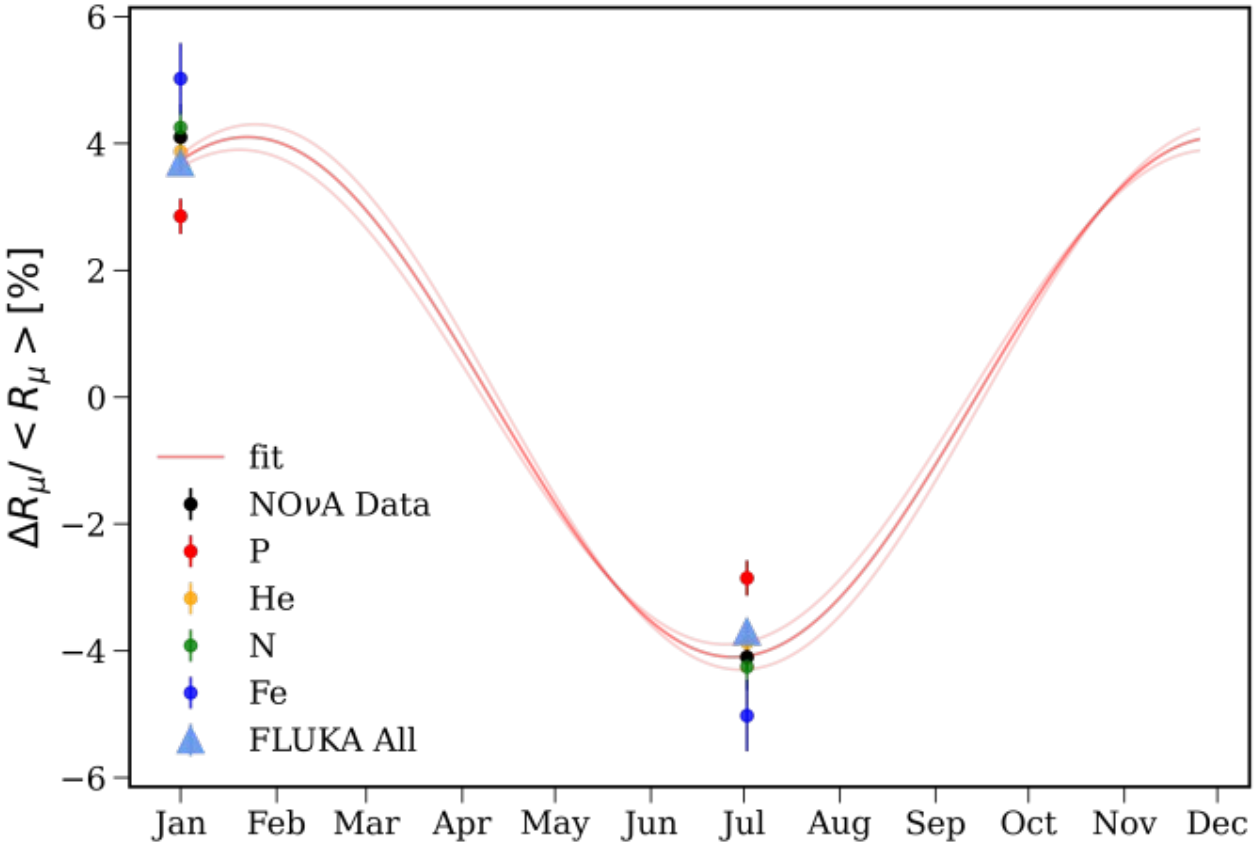
FLUKA (std)

Δx σ_{sw} = 15.46 m,

Δy σ_{sw} = 11.62 m

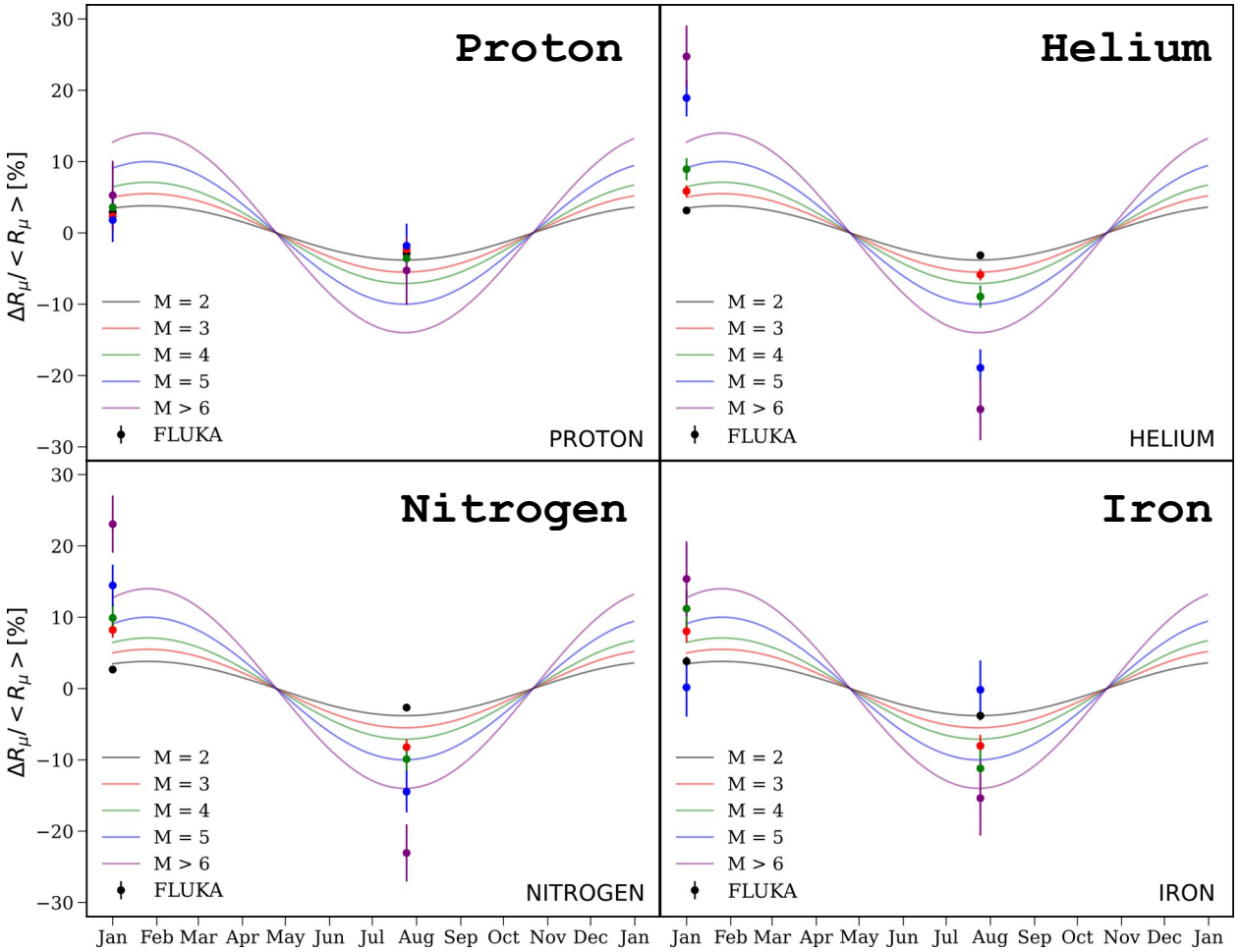
> FLUKA SIMULATIONS RESULTS

> Multiplicity ≥ 2 per Primary species



> FLUKA SIMULATIONS RESULTS

> Multiplicity Dependence per Primary species



Helium is a key element to reproduce the multiplicity!

CORSIKA vs FLUKA

WORK IN PROGRESS

> GEOMETRY

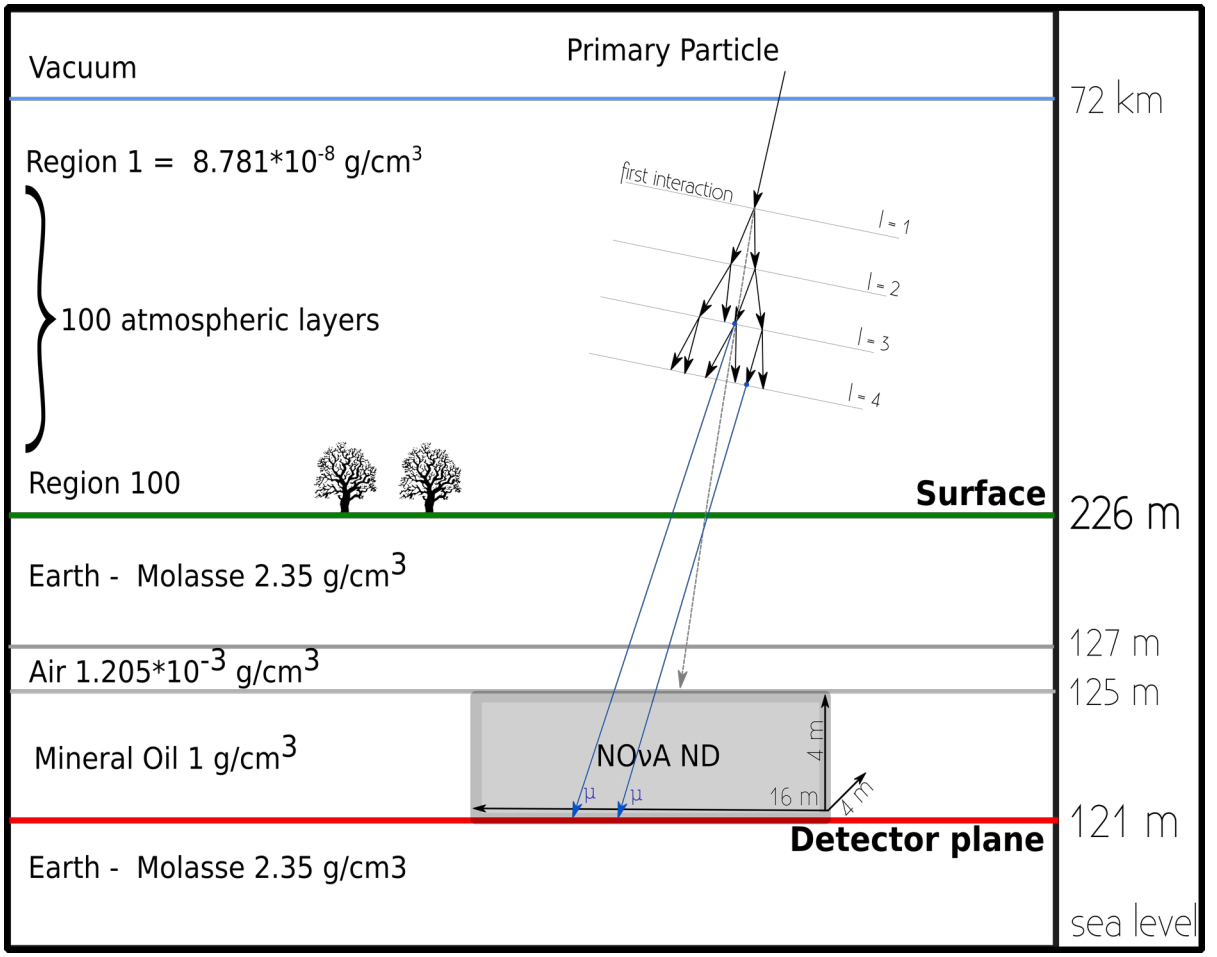
> FLUKA-CERN-4.2.3

> Averaged atmospheres of JAN and JUL 2017

> Data calculated from the temperature and geopotential at 37 pressures level from **European Center for Medium-Range Weather Forecasts (ECMWF).**

> 100 atmospheric layers

> Transport underground



> CORSIKA vs FLUKA

> Geometry

> FLUKA-CERN-4.2.3

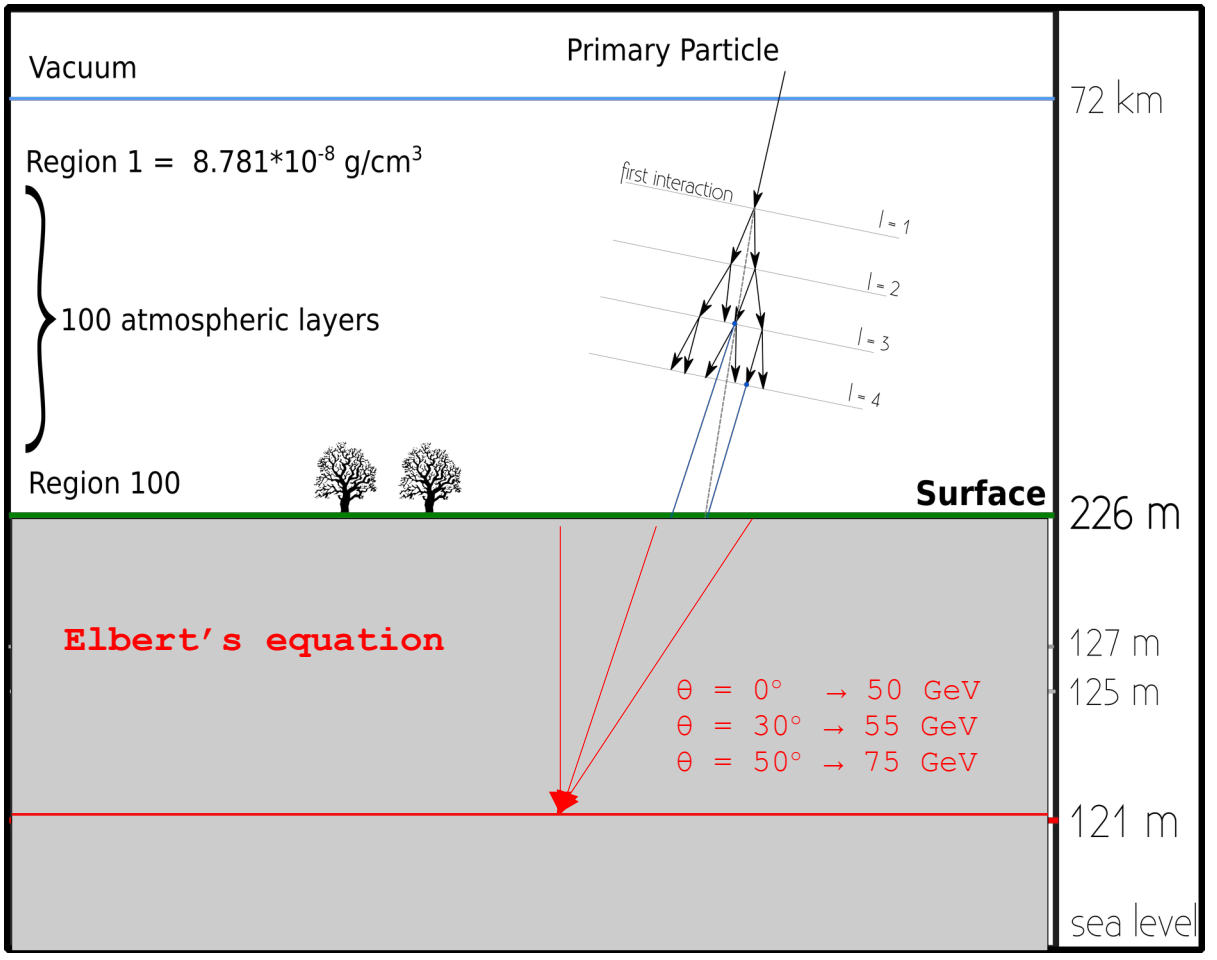
> Averaged atmospheres of JAN and JUL 2017

> Data calculated from the temperature and geopotential at 37 pressures level from **European Center for Medium-Range Weather Forecasts (ECMWF).**

> 100 atmospheric layers

> Transport underground by Elbert's equation

> Angles θ = 0°, 30°, and 50°
  Energy = 50 and 100 TeV

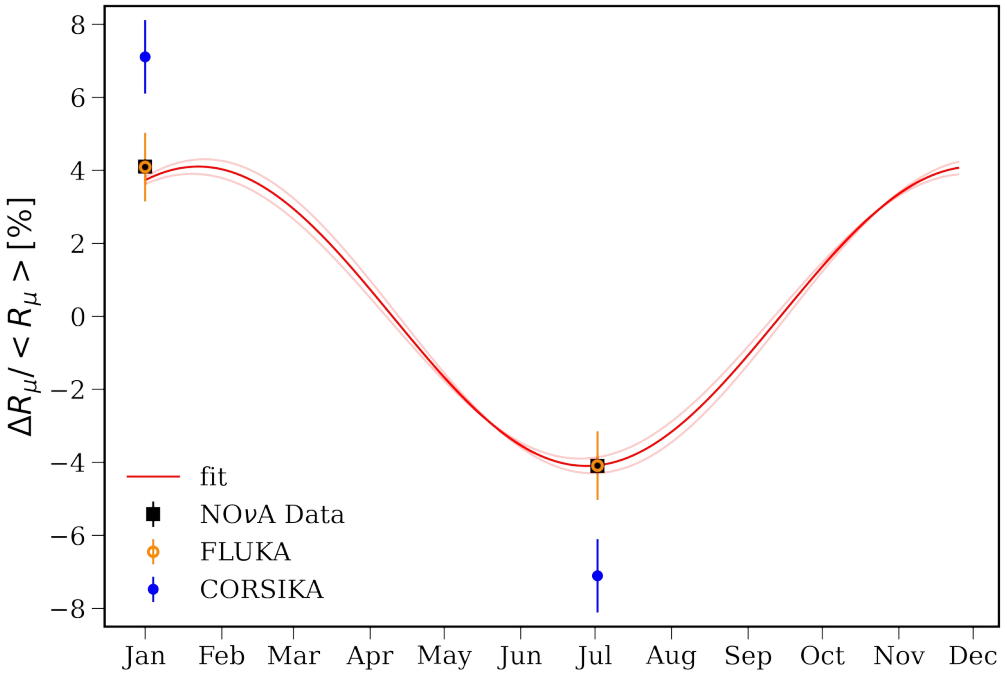


> CORSIKA vs FLUKA

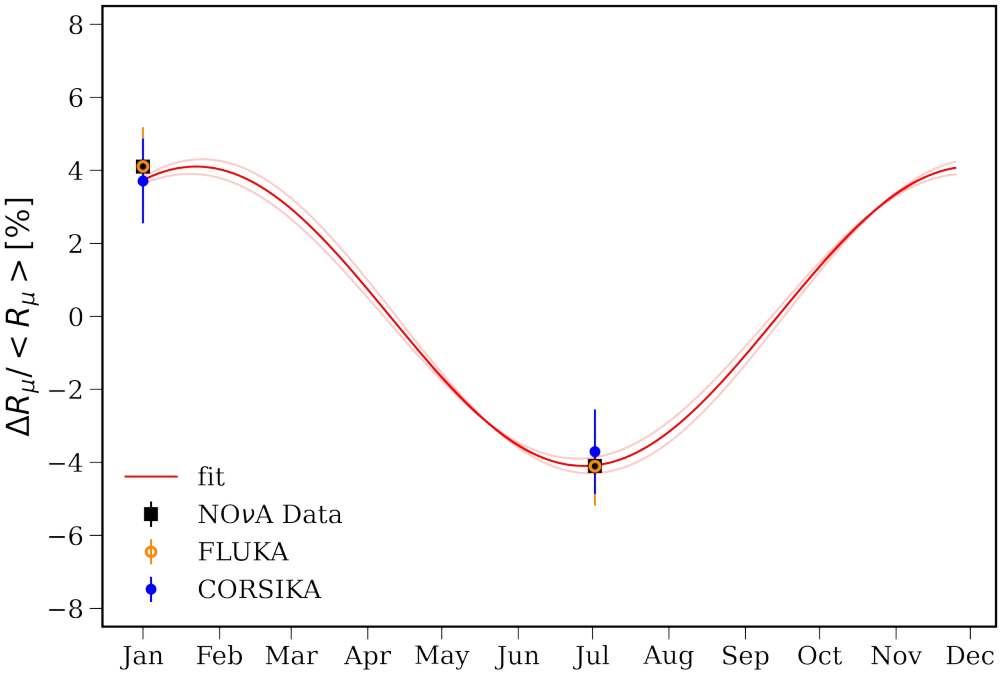
> Multiplicity ≥ 2

θ = 30°

50 TeV



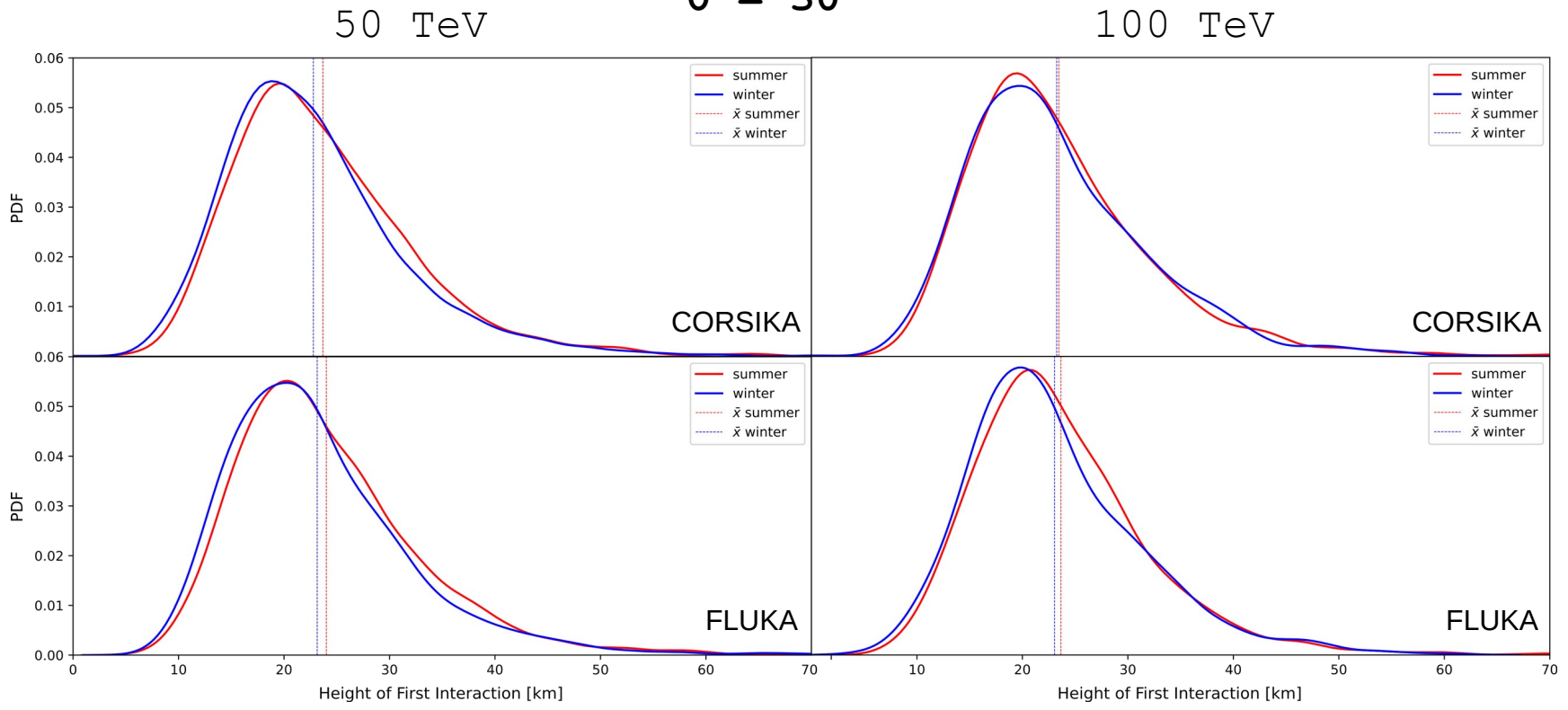
100 TeV



> CORSIKA vs FLUKA

> First Interaction

θ = 30°



> Summary

> We reproduce the multi-muon excess in Winter over Summer observed by the NOνA ND.

> We also reproduce the single-muon excess in Summer over Winter.

> We describe the multiplicity-dependence of the multi-muon seasonal oscillation amplitude.

> The findings of previous publications relating to issues in CORSIKA failing to reproduce the seasonal variation of multi-muons were not confirmed by our work. Nonetheless, we still observe discrepancies between CORSIKA and FLUKA that require further investigation.

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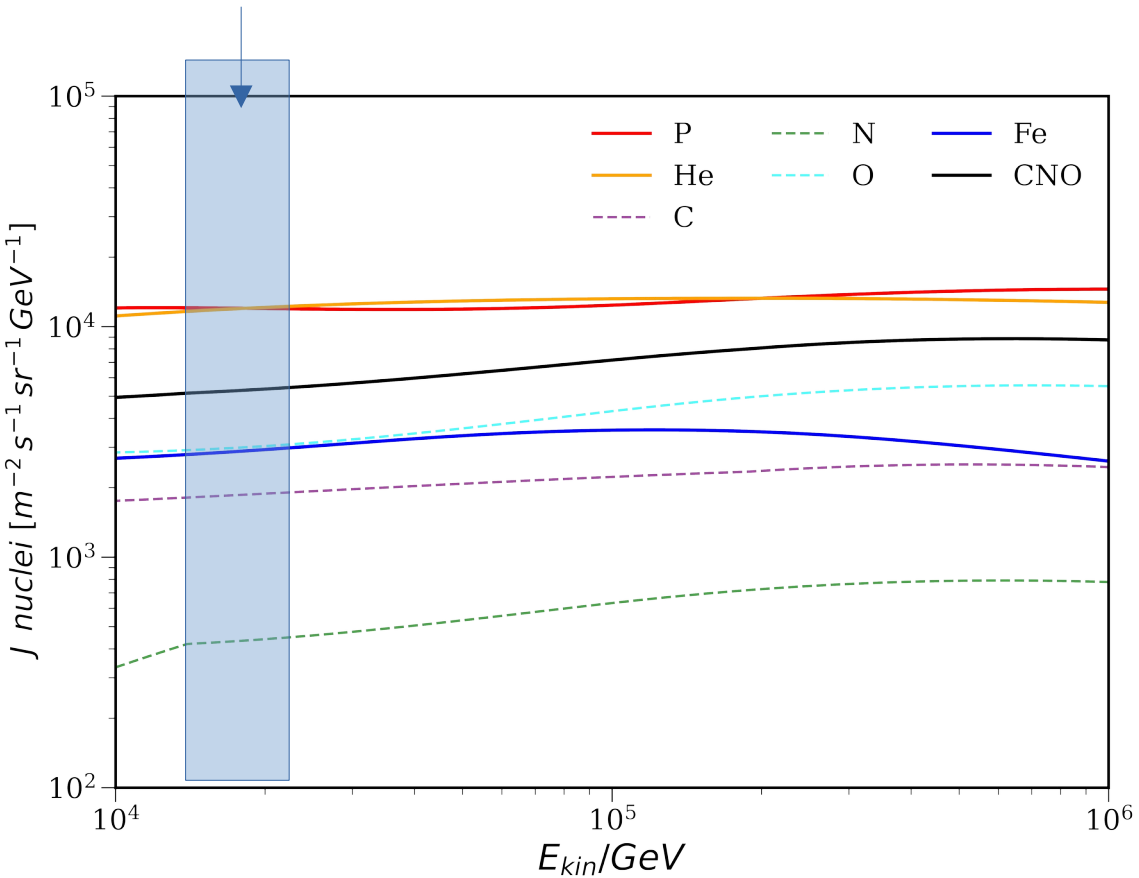
Thank you !!

> BACKUP SLIDES

> Global Spline Model (GSF)

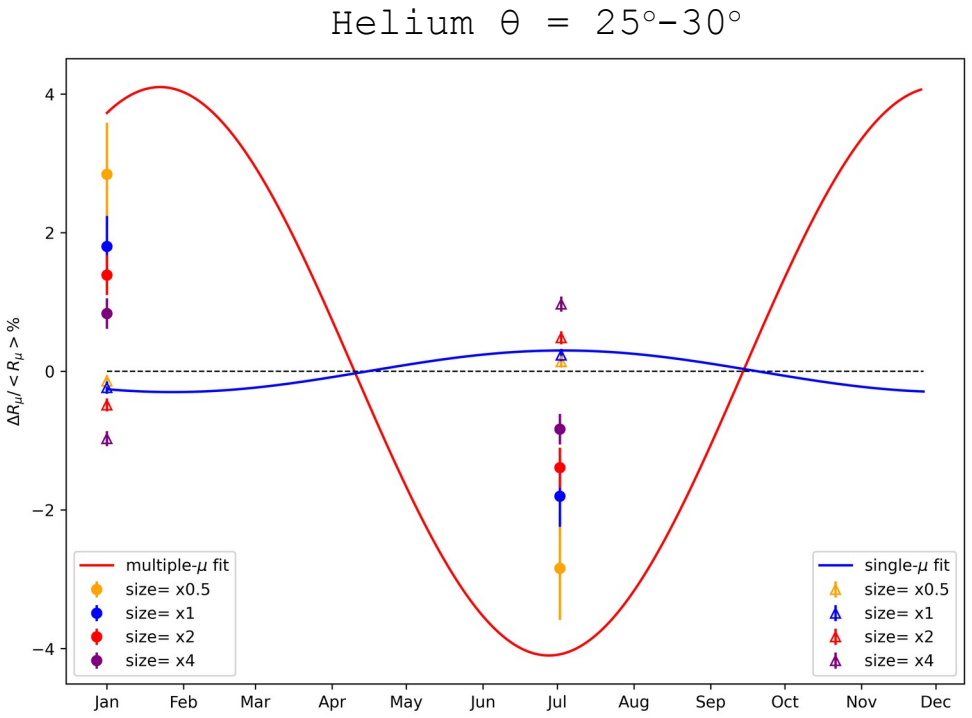
Dominant Energies for our simulations



Dembinski, H. P., et al. PoS ICRC2017 (2018), 533

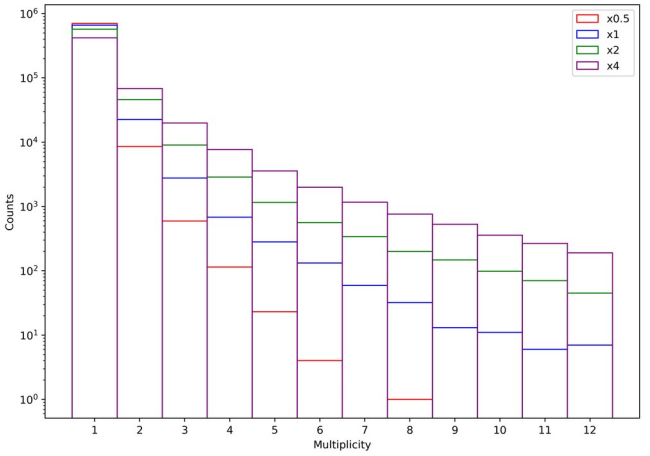
> BACKUP SLIDES

> Detector size dependence



Seasonal Variation for single muons (triangles) and multimuons (points) for multiple sizes of the NOνA ND. Example from pure helium and zenith angle bin 25-30°.

summer



winter