Seasonal Variation in Cosmic Muon Rate at the NOvA Experiment

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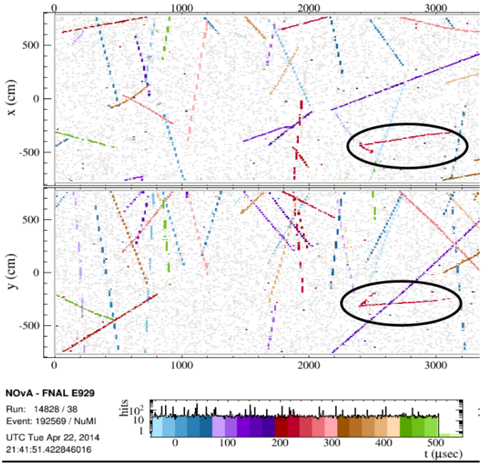
Introduction

- Comsic muons are very important in terms of any neutrino experiments.
- It contributed most as background to neutrino events, especially for surface detectors
- Hence, it is very important to measure the muon flux very precisely.
- One of the key features of the cosmic muon flux is that it varies over the season.



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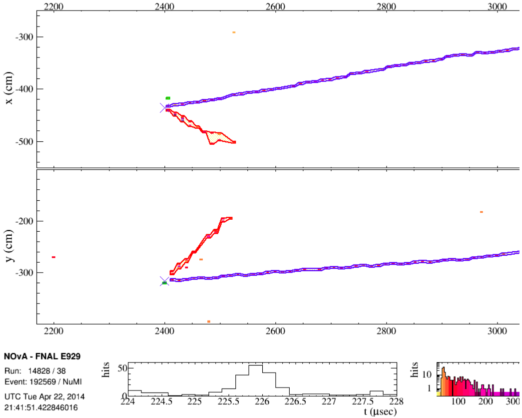
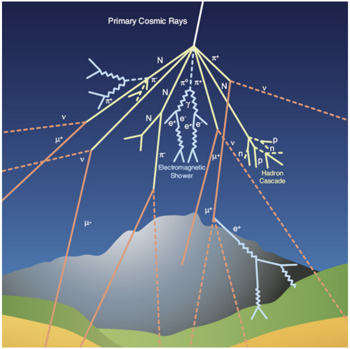


Why cosmic muon varies seasonally?

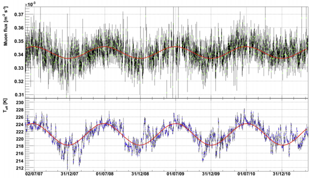
- Development of cosmic showers depends on the atmospheric composition, temperature, air density, earth's magnetic field etc.
- As cosmic muons are mostly produced by decay of kaons and pions, muon rate depends on the probability of decay or interaction of mesons with air molecules.



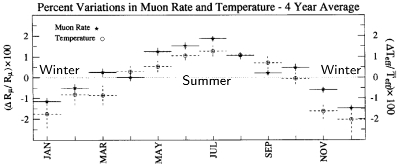
- A higher temperature results in a less dense profile of the atmosphere, causing more pions and kaons to decay and increasing the final muon flux
- Thus, cosmic muon shows a seasonal variation.
  - **Maximum (minimum) muon rate during summer (winter)**

Previous studies

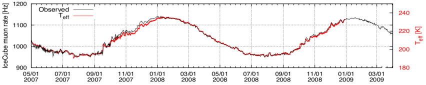
- Cosmic muon seasonal variation is a well measured phenomenon.
- Several experiments, MACRO, AMANDA, Ice Cube presented results on seasonal variation.
- All show a **linear correlation between cosmic muon flux and the mean temperature** of the stratosphere.



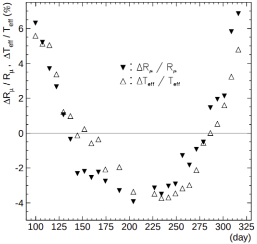
Borexino experiment: JCAP 1205 (2012) 015



MACRO experiment: Astropar. Phys. 7, 109. 1997



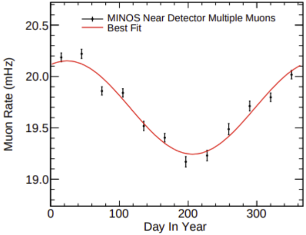
Icecube experiment: arXiv:1001.0776

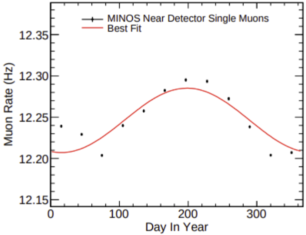


Amanda experiment: Bouchta, A. et al. (AMANDA Collaboration)

Unexpected result from MINOS experiment

- MINOS published a paper in 2015 on seasonal variation of cosmic muon for both of its detectors.
- Multiple muon events showed inverse effect with respect to single muons.
- NOvA ND is also at a similar depth as MINOS ND. This allows us to verify this behavior and gain further insight into it.

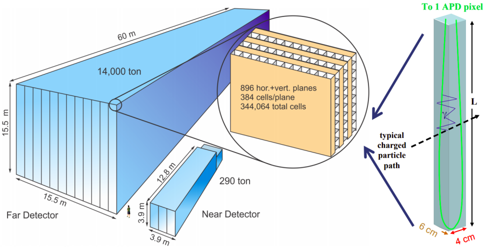


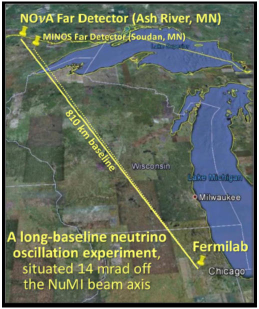


MINOS experiment: Phys. Rev. D 91, 112006. 2015

NOvA detectors

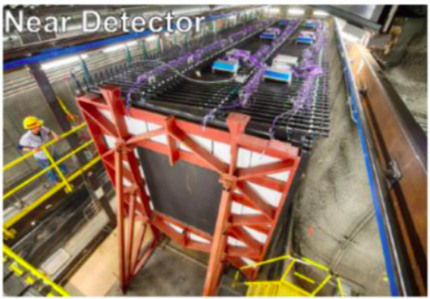
- NOvA is a long-baseline neutrino experiment.
- Two functionally identical scintillator detectors: Near detector and Far detector
- Primary goal is to measure neutrino oscillation parameters by measuring ν_e appearance and ν_μ disappearance
- Suitable for non-oscillation study also: Cosmic ray physics, Search for dark matter, magnetic monopoles
- The basic building block of NOνA is a PVC cell with a looped WLS fiber in it and filled with liquid scintillator.





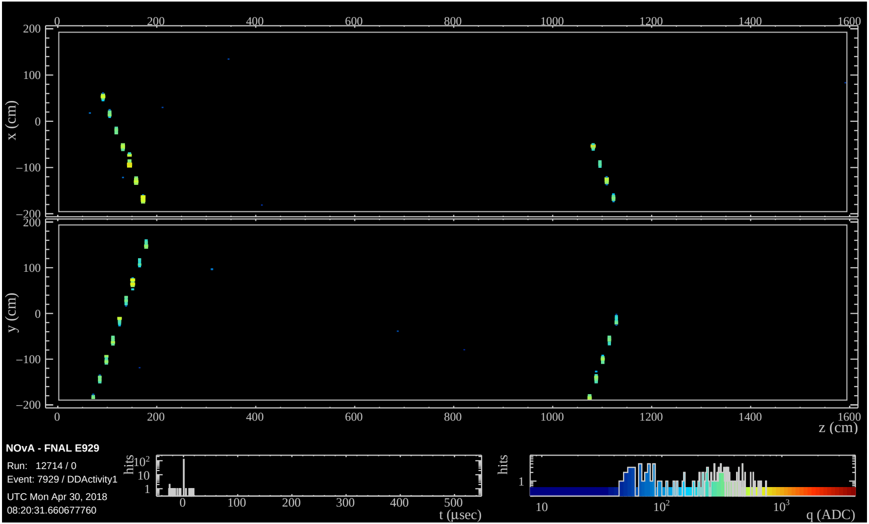
NOvA detectors

NOvA Far Detector



- Near Detector is 300 t, 100 m underground.
- The near detector has the exposure of 35 Hz of comics
- Far detector is 14 kt, on the surface
- Far detector collect cosmics at the rate of 100 kHz

A data-driven trigger collects cosmic muons of every 550 μs at the near detector



Selection of multiple muon event at the ND

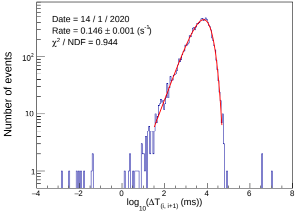
After the trigger data is processed, they are reconstructed using **Multi-Hough Transform** method.

Then few cuts are applied to identify properly recontrsucted multiple muon event:

Time between tracks (start time of ith track - start time of first track)	$\mathbf{\Delta t \leq 100}$ **ns**
Fiducial volume cut (track start and end at distances from the border of the detector)	D $\leq$ 50 cm
Total number of planes cut	nplanes $>$ 10

Finally multiple-muon rate is calculated by fitting **Erlang distribution** with time between two events:

$$R[\lambda, x = log_{10}(\Delta T)] = Ae^{-\lambda 10^x} 10^x \lambda$$

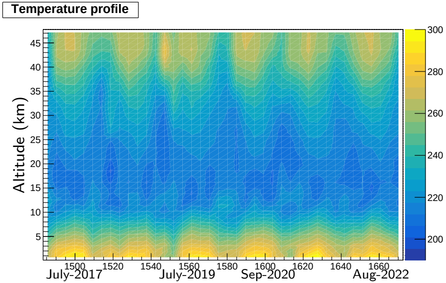


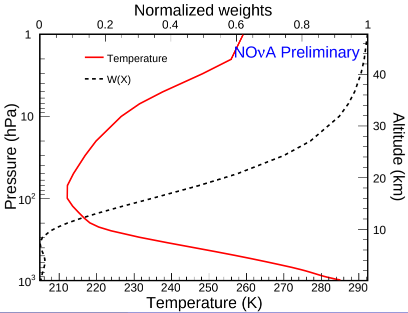
Effective temperature

- We get the atmospheric temperature from ECMWF.
- Atmospheric temperature obeys a non-uniform and complicated profile.
- Mesons and muons are not produced at particular heights.
- To measure the seasonal variation, what temp should we consider? A way to solve this problem is to define an effective temperature, T_{eff}.

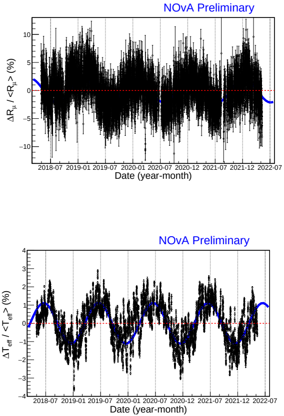
$$T_{eff} = \frac{\sum_{i=1}^{n}[W_\pi(X_i)+W_K(X_i)]T(X)dX_i}{\sum_{i=1}^{n}[W_\pi(X_i)+W_K(X_i)]dX_i}$$

(Astroparticle Physics, 33(3):140–145)

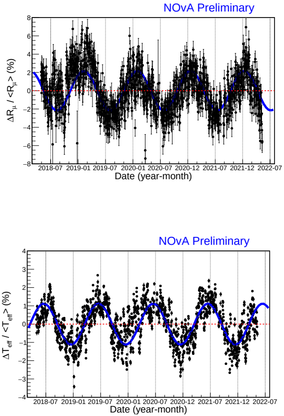




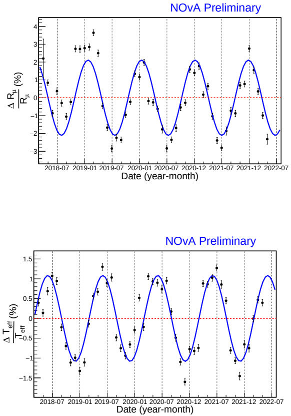
Seasonal variation from ND data (multiple muon events)



Six hour bin



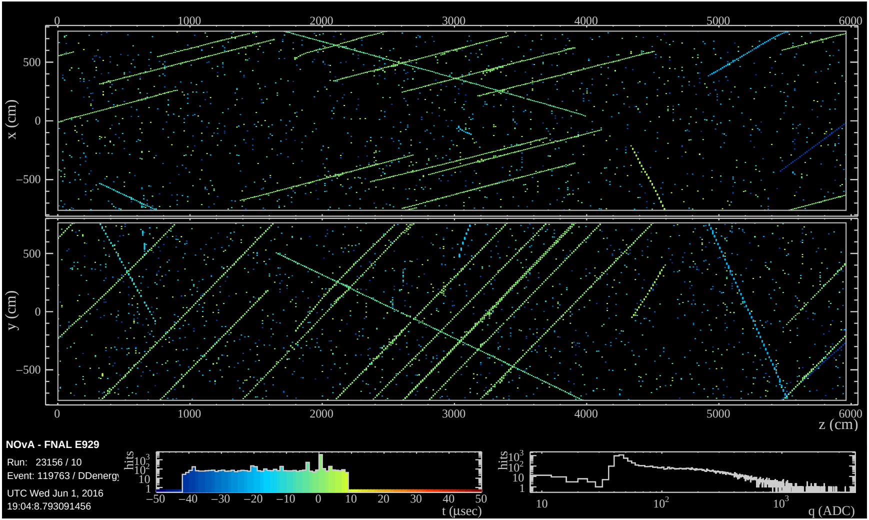
Daily bin



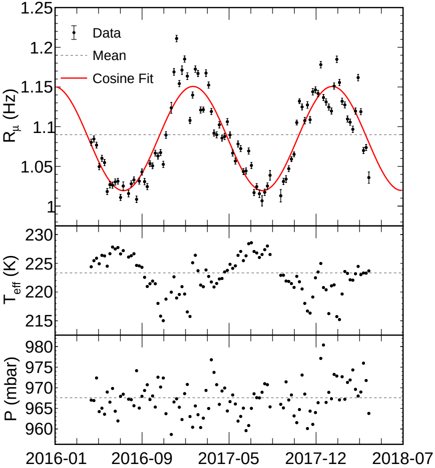
Monthly bin

- We are observing similar behavior as observed by MINOS (maximum rate in winter and minimum rate in summer)

Cosmic muon detection at the FD



Seasonal variation from FD data (multiple muon event)

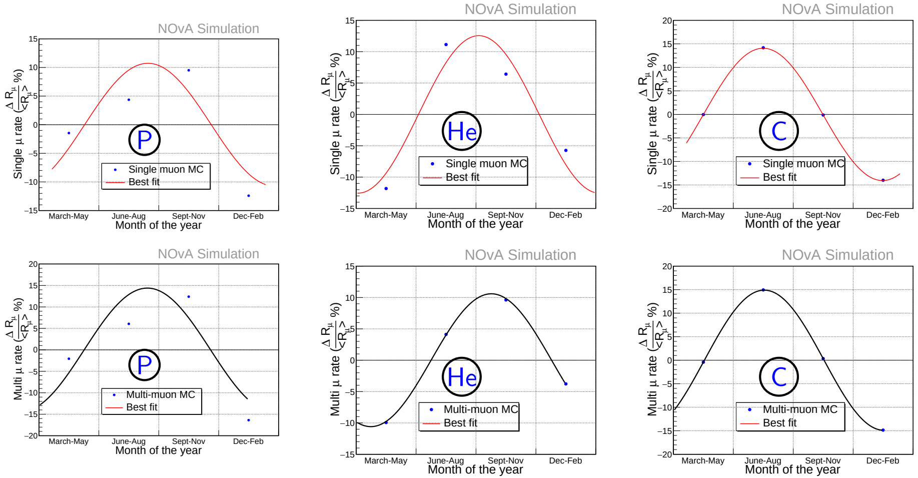


NOvA collaboration: PhysRevD.104.012014

- This is from the NOvA detector on the surface (Far detector)
- Variation of muon multiplicity higher than 15 due to the bigger size of the detector and trigger criteria.
- Amplitude of seasonal effect increases with higher multiplicity and lower zenith angle

Seasonal variation from CORSIKA: On earth surface

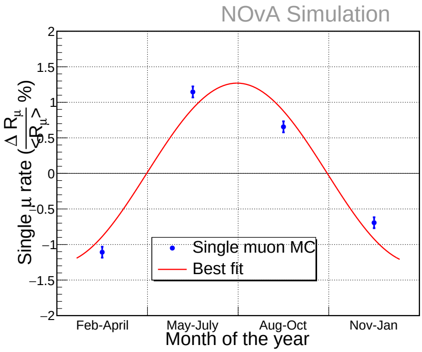
Single muon



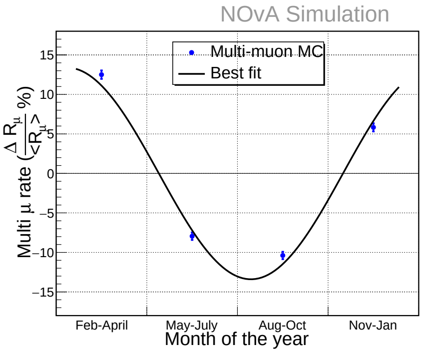
Multiple muon

- Single muon and multi-muon show similar behavior on the earth's surface.

Seasonal variation from CORSIKA: At the ND



Single muon



Multiple muon

- At the detector level, single muon shows the opposite behavior to multi-muon which was reported by MINOS.

Explanation

- Four possible explanations were given in the MINOS paper:
  - Hadronic dimuon decays
  - Temperature effect
  - Anti-correlation of primary and secondary decays
  - **Altitude geometry effect**
- The opposite behavior of multiple muons at infinite size detectors and finite size detector (NOvA ND) justify the altitude geometry effect.
- But this will only happen if the average separation among muons is greater than the size of the detectors.

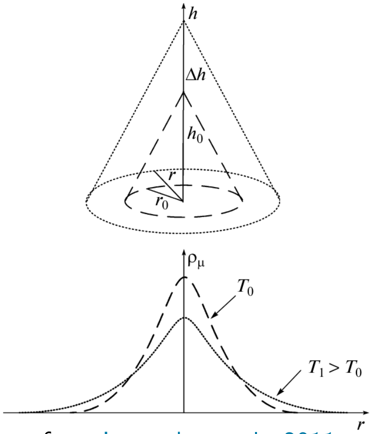


Figure from Lutsenko et al., 2011, doi:10.3103/S1062873811030439

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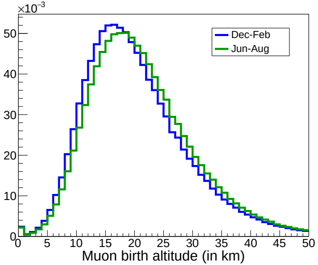
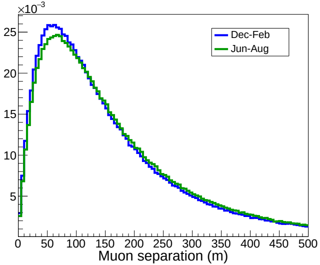
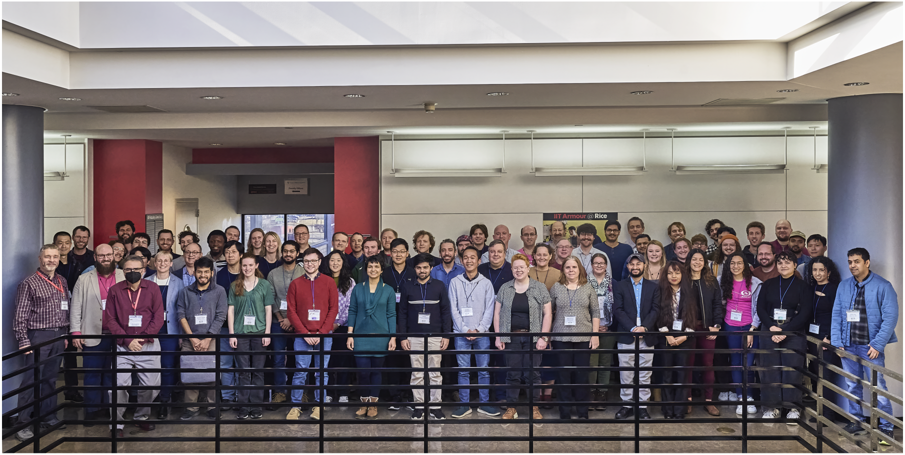




Summary

- Both ND and FD multiple muon rate variation shows anti-correlation with the effective temperature of the atmosphere.
- From the monte-carlo:
  - Seasonal variation of single and multiple muon flux shows similar behavior for infinite size detector.
  - However, they behave oppositely for finite size detectors (NOvA ND).
- The opposite behavior is attributed to the altitude geometry effect.
- We have published two cosmic paper
  - With two years (2015-2017) of ND cosmic data (PhysRevD.99.122004)
  - With three years (2016-2018) of FD cosmic data (PhysRevD.104.012014)
  - Preparing another one with four more years of data from ND cosmic data along with an explanation from Monte-Carlo. Stay tuned!
- Also many exciting results from NOvA on neutrino oscillation parameter measurements, sterile neutrino search, neutrino cross-section measurements, various exotics analyses (https://novaexperiment.fnal.gov/publications/)



NOvA Collaboration, Feb 2024

Thank You!