East-West asymmetry in atmospheric muon fluxes in the Far Detector of NOvA

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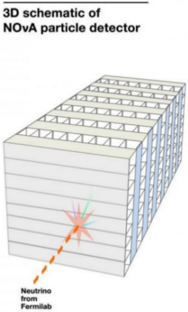
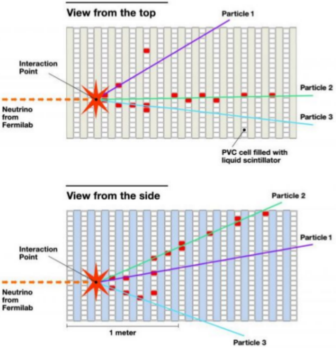
XXV International Scientific Conference of Young Scientists and Specialists

AYSS-2021

NOvA experiment

NOvA is a long-baseline accelerator neutrino oscillation experiment.

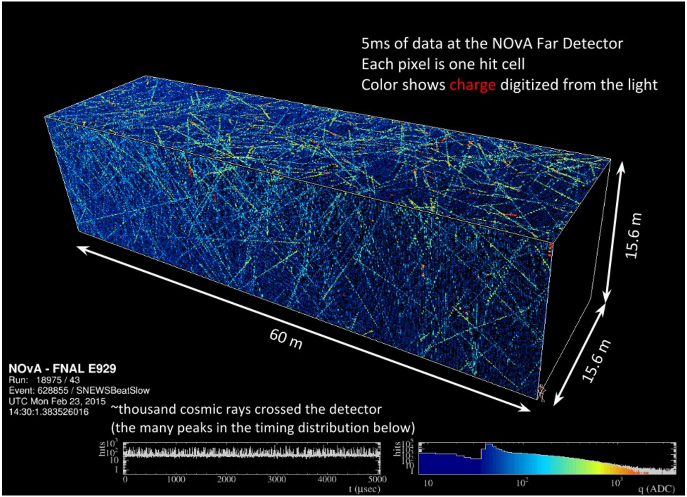




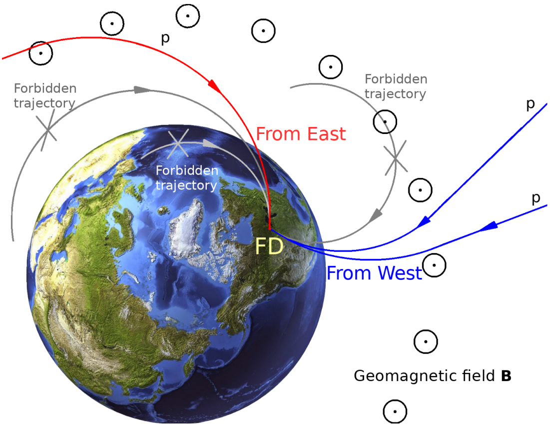
Liquid-scintillator detectors have segmented structure.

NOvA Far Detector

Far Detector is located on the surface and it is huge (14 kt), so rate of cosmic rays is very high.

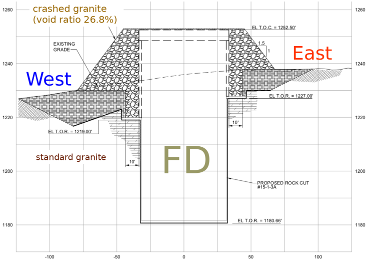


East-West Asymmetry

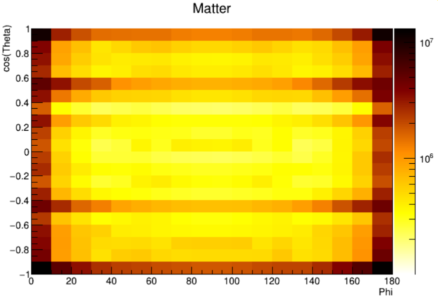


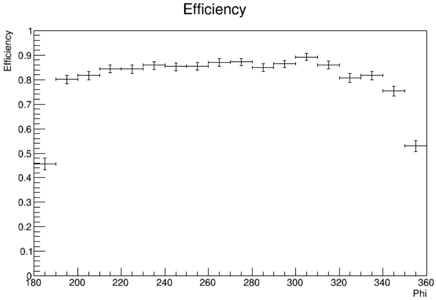
Asymmetry:

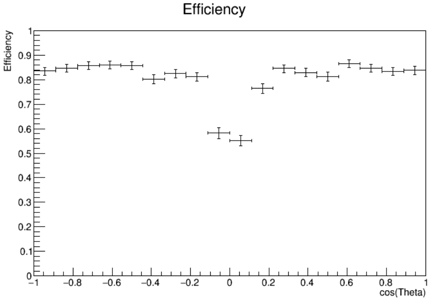
$$A = \frac{\Phi_W - \Phi_E}{\Phi_W + \Phi_E}$$



Overburden effect and efficiency (detector angle notation)







What result we expect

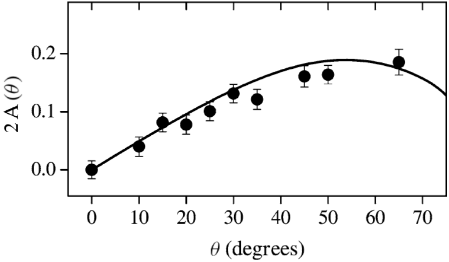


Figure: P.N. Diep *et al.* Measurement of the east-west asymmetry of the cosmic muon flux in Hanoi [$21°01'42.5''$ N, geomagnetic cut-off 17 GV] (2003)

(NOvA FD is located at $48°22'46''$ N, geomagnetic cut-off is about 1-2 GV.)

What result we expect

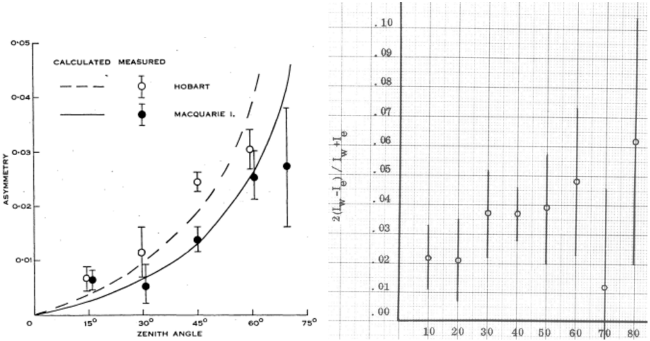


Figure: Left: D.W.P. Burbury, K.B. Fenton. The High Latitude East-West Asymmetry of Cosmic Rays (1951). Hobart [$42°53'00''$ S, 3 GV]. Right: L.L. Nichols. The East-West cosmic ray effect at Corvallis [$44°34'15''$ N, 2 GV], Oregon (1961).

NOvA FD site geomagnetic cut-off is about 1-2 GV. So, I expect $A \sim 1\%$.

East-West asymmetry in the flux detected in the NOvA FD

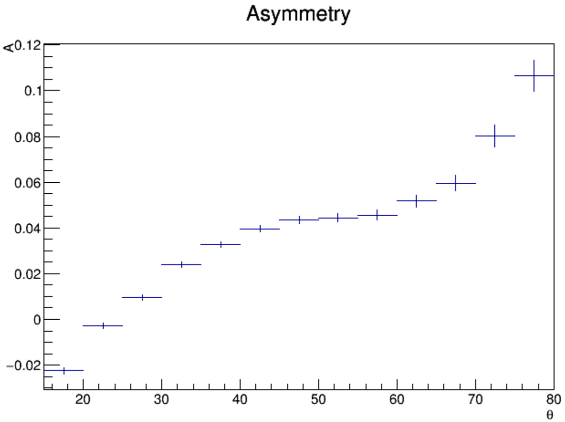


Figure: Cosmic ray muon flux East-West asymmetry in the NOvA Far Detector without any correction to the matter of the surrounding hill. Here I consider

Rough correction to surrounding-induced asymmetry

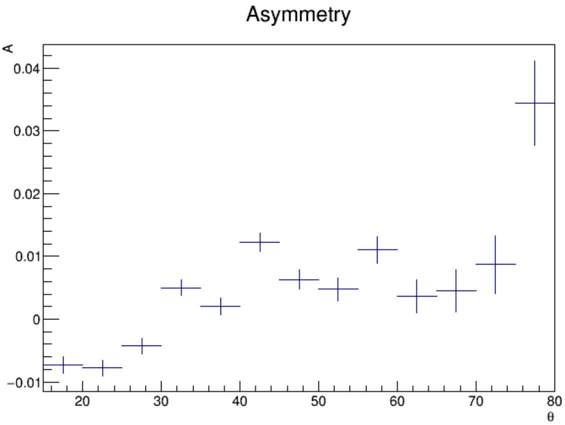


Figure: Roughly corrected EW-asymmetry: for each bin Φ_E^{data} is multiplied by the factor $\Phi_W^{\text{MC}}/\Phi_E^{\text{MC}}$

Flux transformation

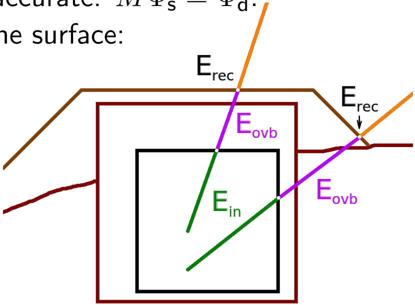
- To measure the asymmetry we need to know 'real', not deformed, muon fluxes on the surface.
- Roughly speaking each track should be counted with weight equal to 1 / probability of that track being registered in our detector with that energy and direction (a function of track direction and position, the energy of muon in the moment of coming to the detector, etc.) and its energy is recalculated. Or more accurate: $M\Phi_s = \Phi_d$.

The energy that stopped muon had on the surface:

$$E_{rec} = E_{in} + E_{ovb}$$

E_{in} reconstruction taking into account multiple scattering inside the detector

E_{ovb} estimation based on overburden description



Tikhonov regularization method

For matrix equation $M\Phi_\mathsf{s} = \Phi_\mathsf{d}$
solution Φ_s can be approximated from minimization

$$\Phi_\mathsf{s} = \underset{x}{\operatorname{argmin}} ||Mx - \Phi_\mathsf{d}||$$

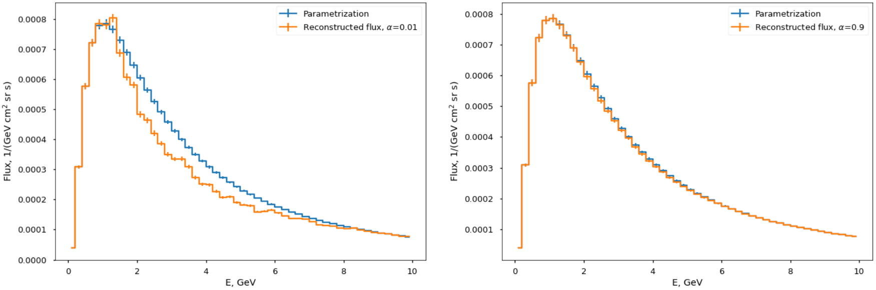
but if $\Phi_\mathsf{d} \to \Phi_\mathsf{d} + \delta\Phi_\mathsf{d}$ it diverges.
Regularization is when we suggesting that our approximate solution Φ_s is similar to some function $\widetilde{\Phi}_\mathsf{s}$:

$$\Phi_\alpha = \underset{x}{\operatorname{argmin}} \left[||Mx - \Phi_\mathsf{d}||^2 + \alpha ||x - \widetilde{\Phi}_\mathsf{s}||^2 \right],$$

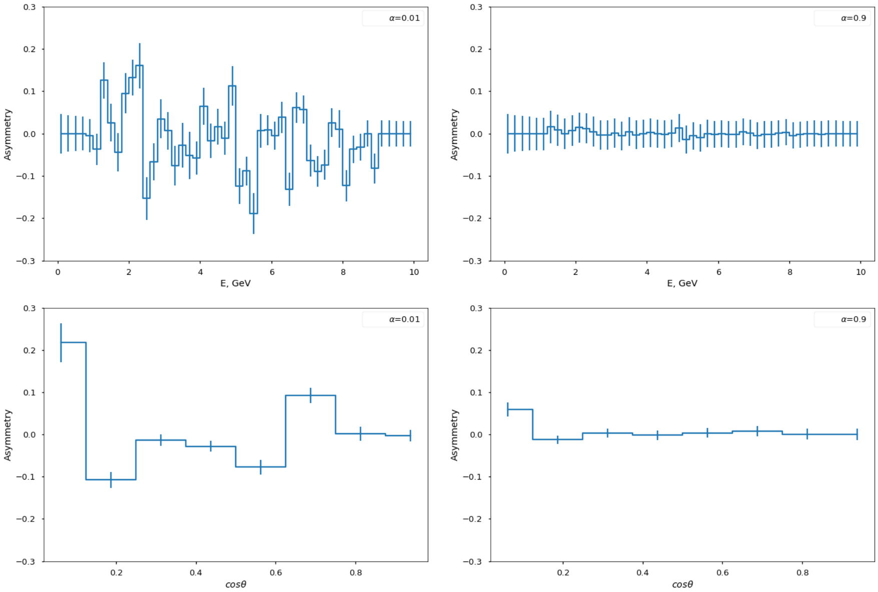
α characterises how tight we want be connected to $\widetilde{\Phi}_\mathsf{s}$.

Regularization results

So we need as $\widetilde{\Phi}_s$ any description of spectra (where East-West asymmetry isn't taken into account, for example). I use a parametrization from [?]. You can see an example of regularization results here:



A. Ariga *et al.* A Nuclear Emulsion Detector for the Muon Radiography of a Glacier Structure // Instruments, 2018.


α=0.01
α=0.9
α=0.01
α=0.9
Asymmetry
E, GeV
cosθ
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0
2
4
6
8
10
0.2
0.4
0.6
0.8

Problems with regularization

- The bigger α we chose, the less difference we get between $\widetilde{\Phi}_\mathsf{s}$ and the solution.
- So, the main question for now is:
  Can we actually measure East-West asymmetry with this method, or the result will be always proportional to the deliberately chosen α?
- We can probe different artificial asymmetries:
  if we get X, when put A and α, then $A = A(X, \alpha)$ and we can interpolate this function and find the value of it for real X.
- The problem with this idea is that $A = A(X, \alpha)$ can be wide various for different forms of A.

Other ideas / Plans

- If we add an artificial East-West difference to the MC flux, simulate particles pass the detector with usual reconstruction chain and tune its size till the result matches the data, then we'll measure the size of the effect, and we could also use this to estimate its error.
- Then maybe we can return to regularization with found asymmetry form and get more accurate result.

Summary

- The Far Detector of the NOvA experiment provides an opportunity to study geomagnetic effects through the atmospheric muon fluxes measuring.
- Surrounding asymmetry should be taking to account.
- The expected value of atmospheric muon flux East-West asymmetry is about 1%.
- Regularization technic of surface flux reconstruction (unfolding) has some problems.
- Work on straight-forward flux transformation (folding) method is in progress.

Under grant RSF 18-12-00271

Thank you!

Uncertainties

$\Phi_0(E, \theta, \phi)$ - measured muon flux
$\varepsilon(E, \theta, \phi)$ - reconstruction efficiency, $\delta\varepsilon$ - its uncertainty

$$\Phi_C = \frac{\Phi_0}{\varepsilon}$$

So

$$\frac{\delta \Phi_C}{\Phi_C} = \frac{\delta \Phi_0}{\Phi_0} - \frac{\delta \varepsilon}{\varepsilon}$$

Considering that the measured flux (i.e. number of tracks in the bin) is Poissonian:

$$\sigma_C = \Phi_C \sqrt{\frac{\sigma_0^2}{\Phi_0^2} + \frac{\sigma_\varepsilon^2}{\varepsilon^2}} = \Phi_C \sqrt{\frac{1}{\Phi_0} + \frac{\sigma_\varepsilon^2}{\varepsilon^2}}$$

Uncertainties

How we calculate each bin in our final flux histogram:

$$C = \sum_i n_i W_i,$$

where n_i – a number of muons in the i-th bin of the efficiency, $W = 1/\varepsilon \equiv N_{\text{sim}}/N_{\text{rec}}$.

$$\langle \delta C^2 \rangle = \sum_i \langle \delta W_i^2 \rangle n_i^2 - \\ - \sum_i W_i^2 \langle \delta n_i^2 \rangle$$