East-west asymmetry effect in atmospheric muon flux in the Far Detector of NOvA

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Introduction

The Far Detector (FD) of the NOvA experiment is located on the surface unlike most of the neutrino detectors. Frequency of cosmic ray detections in the FD is ~100 kHz, so the atmospheric muon fluxes and their angular dependencies can be measured and explored with high statistics.

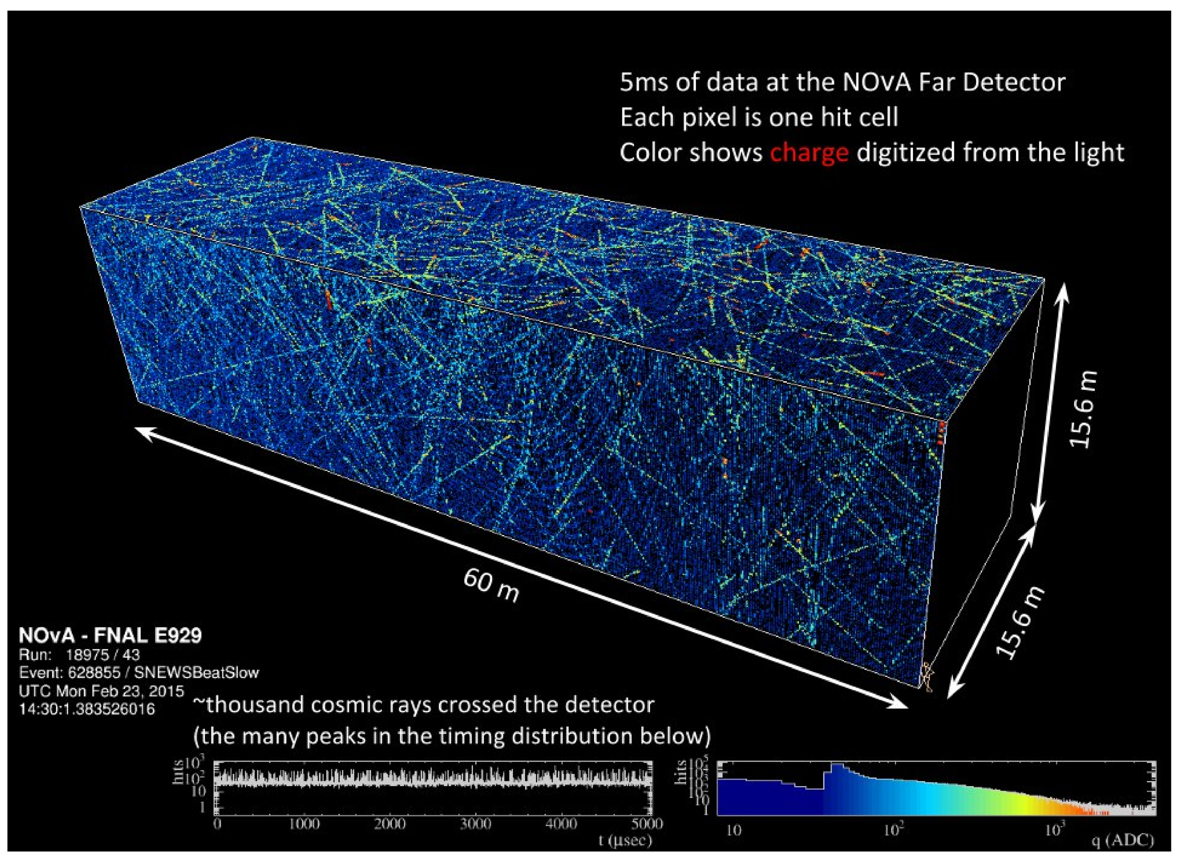


Figure 1: Event display of the Far Detector with many cosmic ray tracks

The East-West asymmetry in the cosmic ray muon flux is connected to the magnetic field of Earth. High latitude of the FD site can help NOvA measurements bring new knowledge on the subject.

Phenomenon

Muons constitute one of the main parts of the secondary cosmic rays. They are born along with atmospheric neutrinos:

$$p + N \to \pi^{\pm}, K^{\pm} + X; \qquad \pi^{\pm}, K^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}).$$

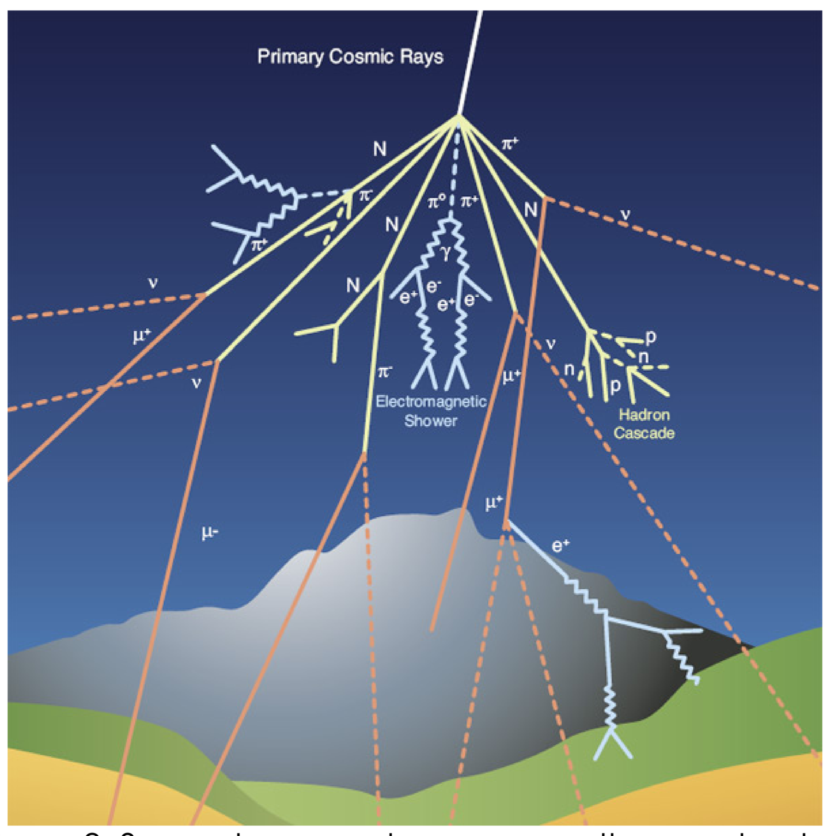


Figure 2: Secondary cosmic ray generation mechanism

The geomagnetic field is directed to the North Pole. About 99% of primary cosmic rays have a positive charge. In the Northern Hemisphere positively charged particles deviate to the right affected by the Lorentz force.

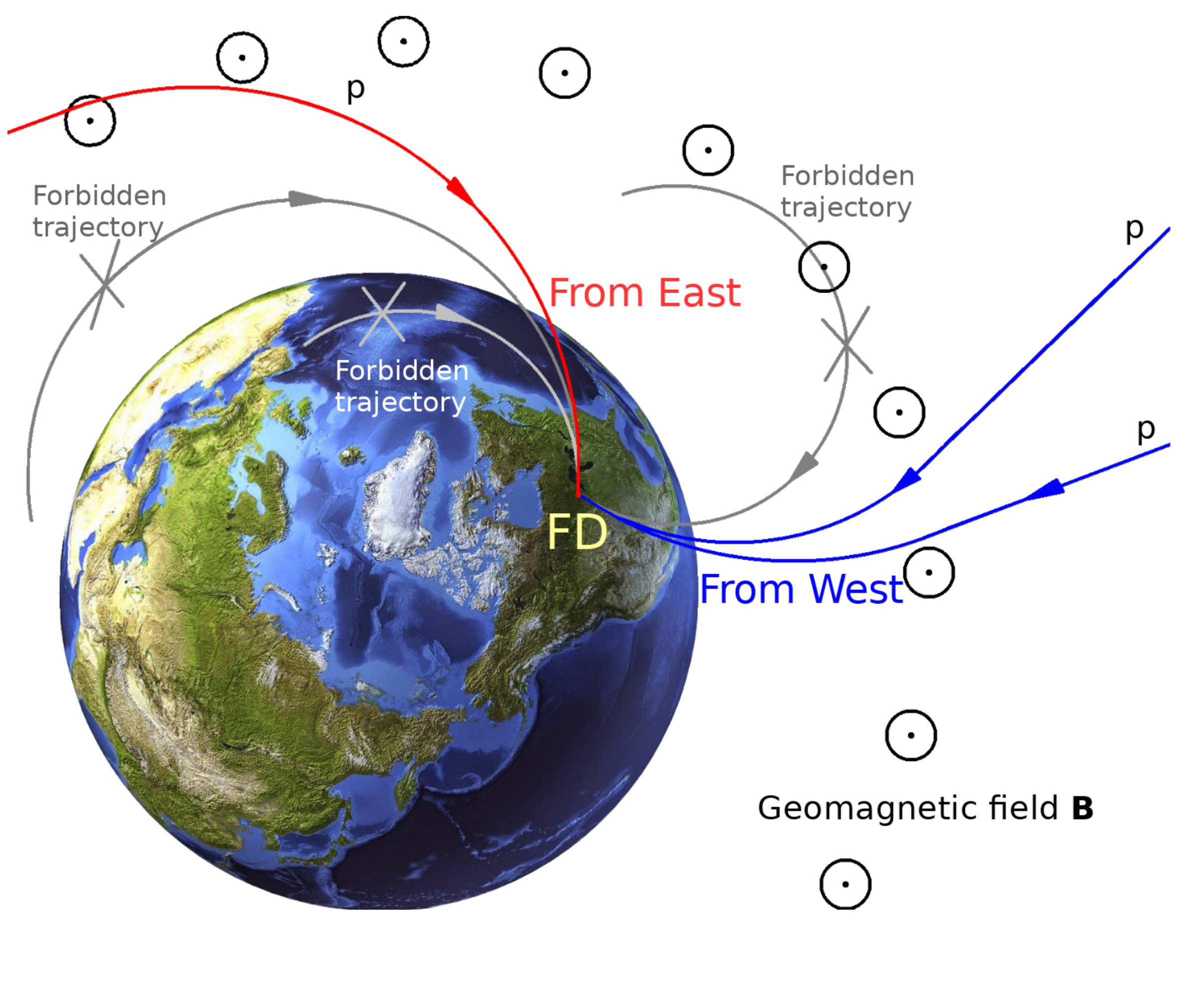


Figure 3: East-West asymmetry of cosmic rays

It means that for the particles coming to a certain point on the Earth from the East, some of the trajectories are forbidden, and the cosmic ray flux from the East is smaller than one from the West. This effect, called the East-West cosmic ray asymmetry, is less significant for the particles with higher energies.

Overburden asymmetry

The East-West asymmetry study in NOvA is complicated by the fact that the FD overburden and the rock surrounding it are also asymmetrical.

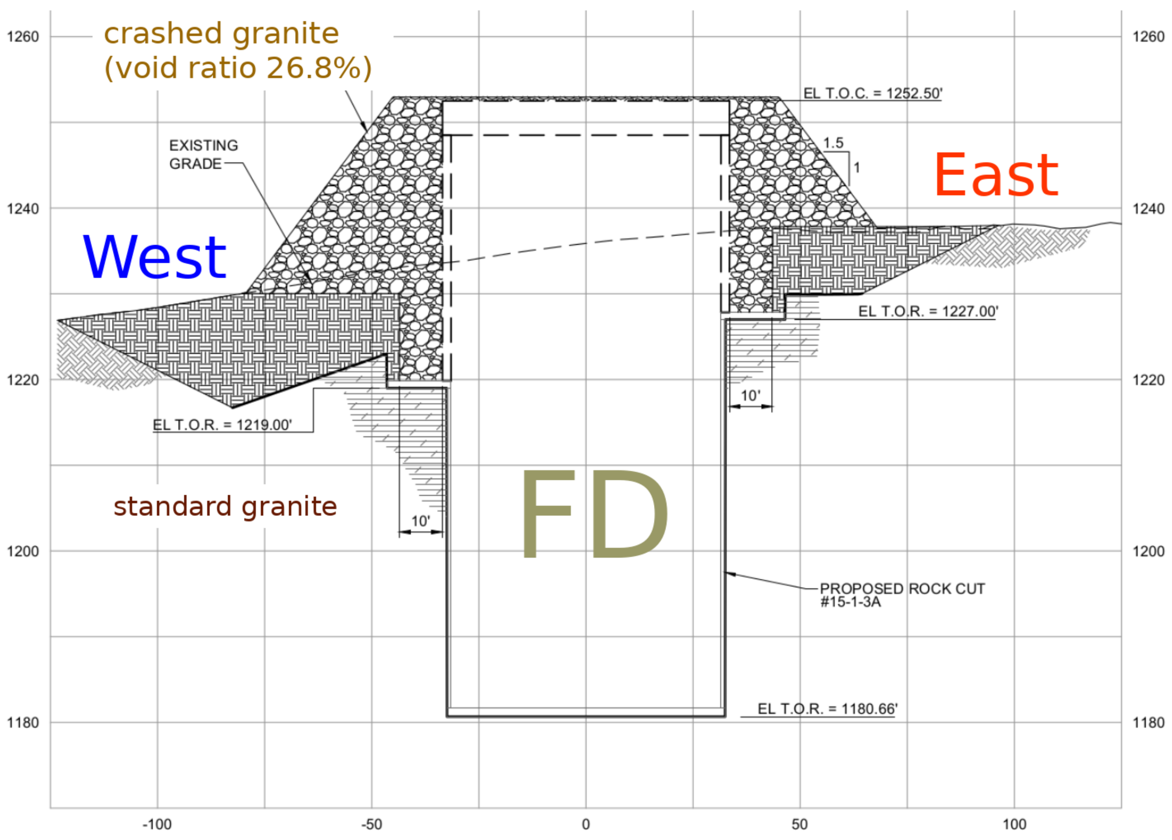
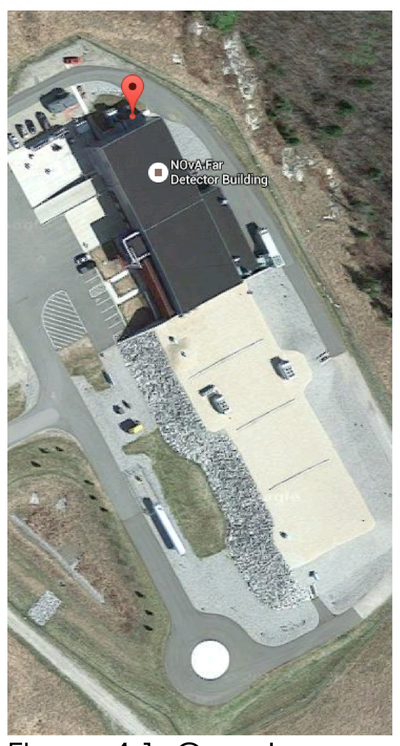


Figure 4: Asymmetry of the hill around the FD



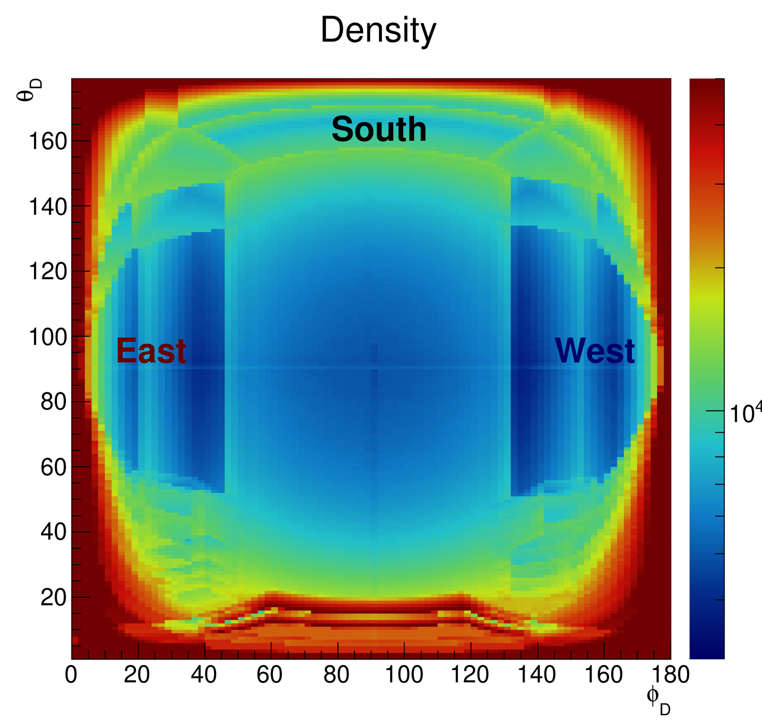


Figure 4.1: Google-map view of the FD site at Ash River, MN.
Figure 4.2: Distribution of matter density (g/cm^2) from the center of the FD along various directions (detector coordinate system, Z-axis is oriented to North along with the detector)

Energy reconstruction

To reconstruct an energy that a certain muon had on the surface we used the following procedure. Part of the energy, which is lost inside the detector, is reconstructed by using the BreakPointFitter package, which takes into account multiple scattering. Estimation of the other part is based on the surrounding matter description and specific energy loss in it.

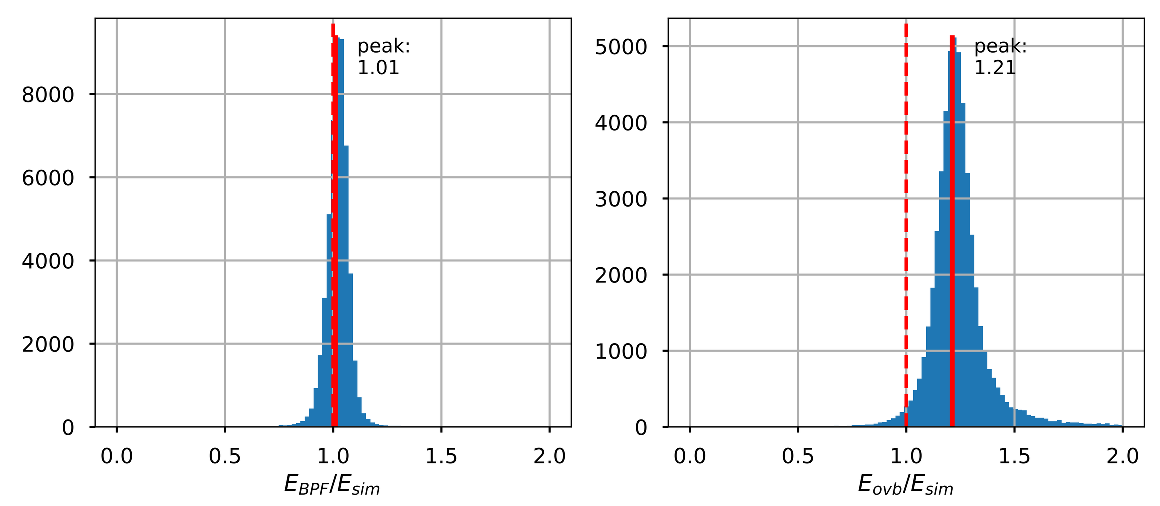


Figure 5: Relative resolution of stopping muon energy reconstruction: left - inner part, right - outer part. Systematic error is to be understood

Only muons, stopping inside the fiducial volume of the FD, are used in this analysis, because their energy can be estimated. Also, energies of through-going muons are higher in general, and the geomagnetic effect on them should be less marked.

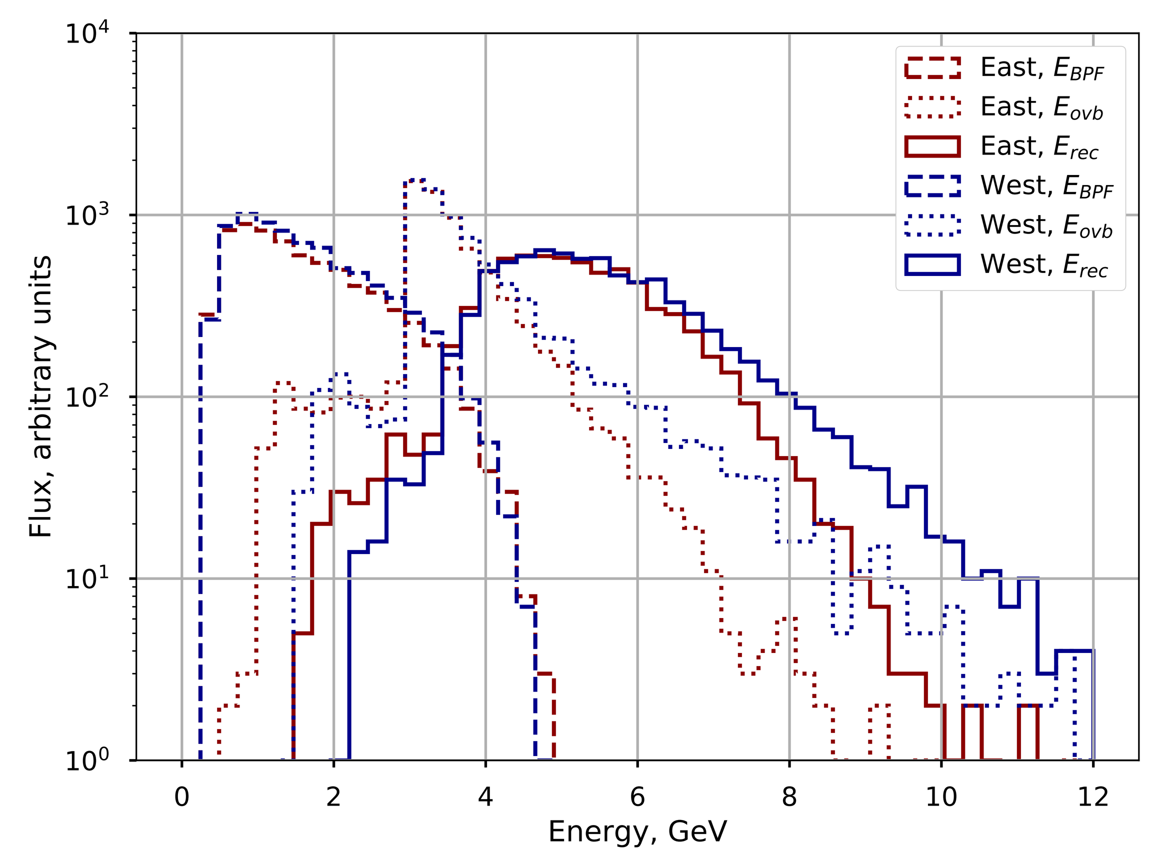


Figure 6: Energy spectra of detected stopping muons

Efficiency estimation

Because of the segmented structure of the detector, which consists of only two sets of the PVC tubes: horizontal and vertical, reconstruction efficiency is significantly less in corresponding angular regions. Tracks with $\theta_D < 5^{\circ}$ or $\phi_D = 180^{\circ}, 360^{\circ}$ are excluded from the analysis.

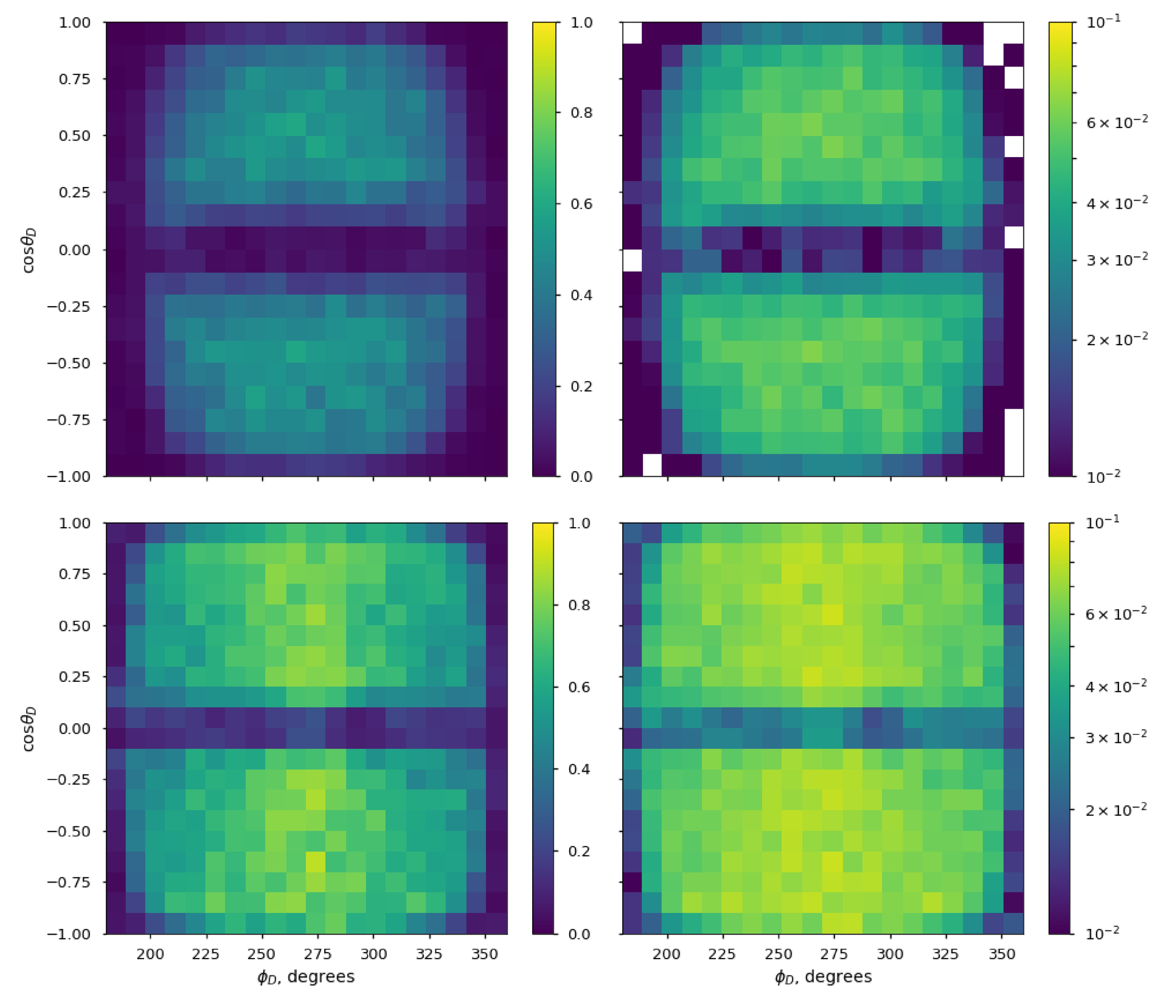


Figure 7: Reconstruction efficiency (left) and its uncertainty (right) for muons as a function of detector angles, for 2 intervals of reconstructed energy (inner part): $E_{\mu} < 1$ GeV (top) and 1 GeV$< E_{\mu} < 2$ GeV (bottom)

Reweihted fluxes

In order to include geometry-induced asymmetry we count each track with weight equal to $1/\epsilon$, where ϵ is reconstruction efficiency, a function of track direction, energy of muon in the moment of coming to the detector, etc.

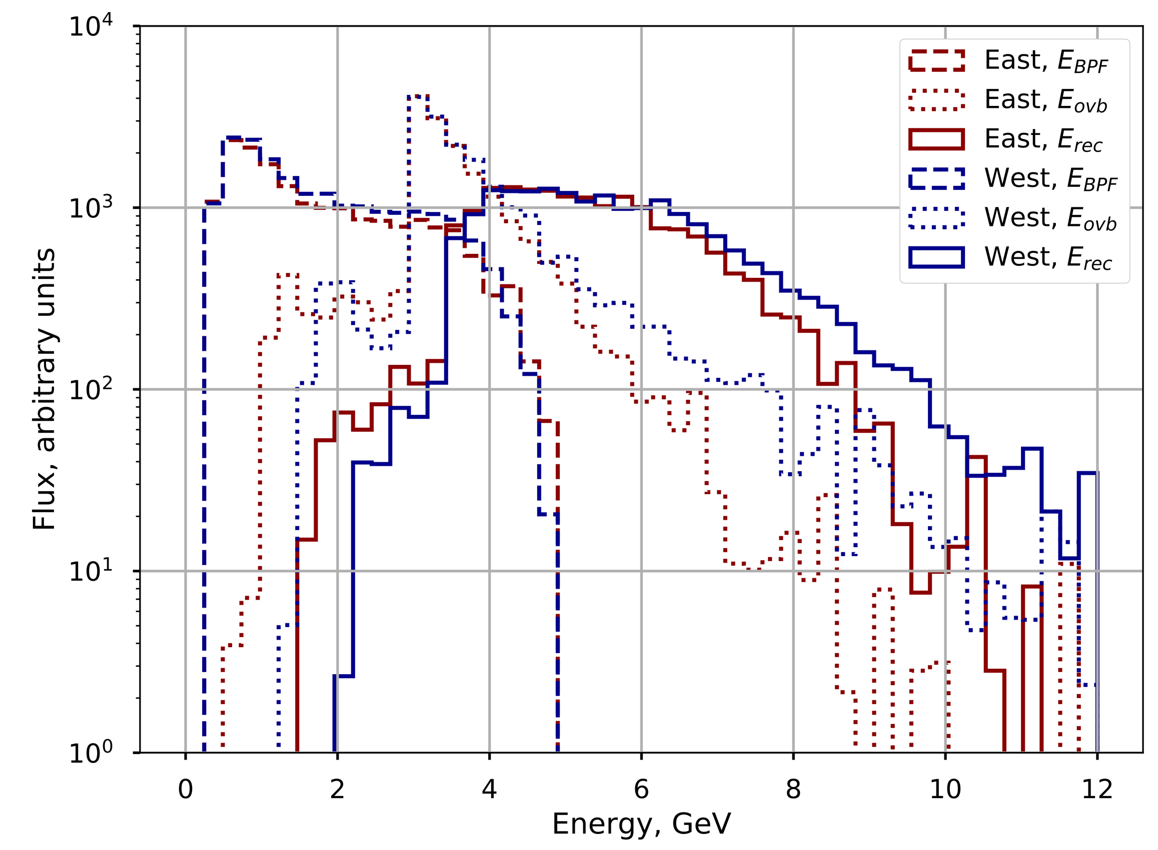


Figure 8: Reweighted energy spectra of stopping muons

Asymmetry

East-West asymmetry is $A = 2 \cdot \frac{W - E}{W + E}$, where W and E are CR fluxes from the West and the East respectively. For our preliminary analysis we are looking at $\pm 10^{\circ}$ spread along these directions.

I see two ways to calculate asymmetry: one of them includes unfolding and the other one uses fitting.

Tikhonov regularization

If Φ_s is flux on surface, Φ_d is reconstructed flux, then we can write matrix equation: $M\Phi_s = \Phi_d$, where $M = M_{eff}M_{mat}$ is transformation matrix, M_{eff} characterizes efficiency of reconstruction, M_{mat} characterizes effect of surrounding matter.

So we want to make an inverse transformation. In most cases exact the inverse matrix doesn't exist. Solution Φ_s can be approximated from minimization

$$\Phi_s = \underset{x}{\mathrm{argmin}} \|Mx - \Phi_d\|$$

but if $\Phi_d \to \Phi_d + \delta\Phi_d$ it diverges.

We suggest that our approximate solution Φ_s is similar to some function $\widetilde{\Phi}_s$:

$$\Phi_s = \Phi_{\alpha} = \underset{x}{\mathrm{argmin}} \left[\|Mx - \Phi_d\|^2 + \alpha \|x - \widetilde{\Phi}_s\|^2 \right] \Rightarrow$$
$$x = \widetilde{\Phi}_s + (M^T M + \alpha I)^{-1} M^T (\Phi_d - M\widetilde{\Phi}_s),$$

α characterises how tight we want to be bound to $\widetilde{\Phi}_s$.

Fitting method

There are theoretical calculations of muon flux on the surface, let's take one: Φ_s^{th}. If we can make suggestions about functional dependency of asymmetry on arguments (energy and angles) $A(E, \phi, \theta, \text{parameters})$, we can fit parameters and find actual asymmetry like this:

1. add asymmetrical part to theoretical calculations: $W = \Phi_s^{th}(1 + A/2)$, $E = \Phi_s^{th}(1 - A/2)$,
2. make MC with this as initial flux,
3. bring it through the reconstruction and selection chain,
4. minimize the difference between the result and the data and extract the parameter values.

We can also take a ready-made MC made by the CRY model as Φ_s^{th}, because it doesn't include the East-West effect.