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

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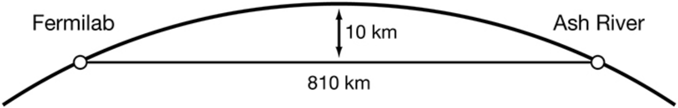
NuMI Off-axis ν_e Appearance (NOvA) experiment

Figure: Two detectors: Near Detector in Fermilab and Far Detector near Canada

NOvA experiment



The NOvA experiment goals:

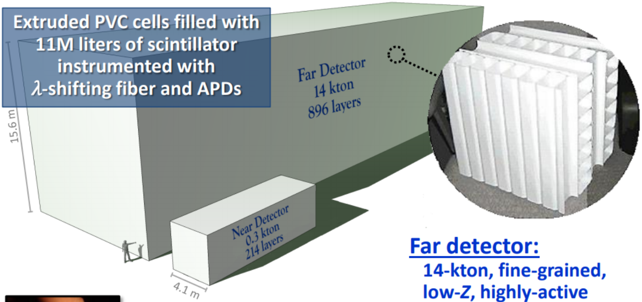
- neutrino mass hierarchy investigation
- θ_{13} measurement in ν_e appearance mode
- constraining of δ_{CP}
- θ_{23} rectification
- precise measurement of $|\Delta m^2_{32}|$
- other physics:
  - neutrino cross section measurement
  - supernova neutrino observation
  - magnetic monopole search
  - cosmic ray studies
  - ...

NOνA

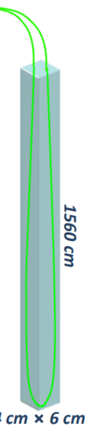
810 km baseline
14 mrad off-axis
$E_\nu \sim 2$ GeV
Detectors:
Near: 330 tons
Far : 14 ktons

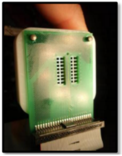
Detectors

Liquid scintillator (mineral oil) in the segmented structure of PVC



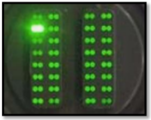
Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs





32-pixel APD

Fiber pairs from 32 cells



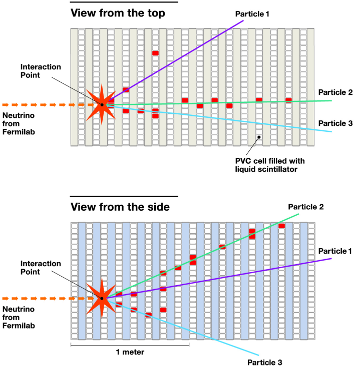
Far detector:

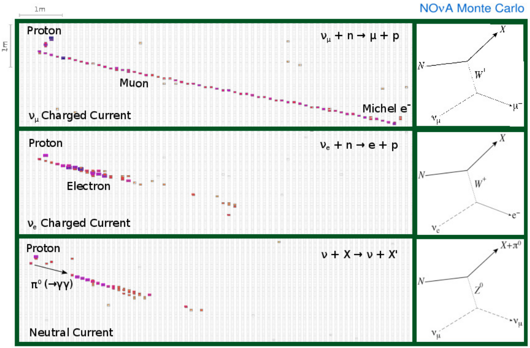
14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ *344,000 channels*

Near detector:

0.3-kton version of the same
→ *20,000 channels*

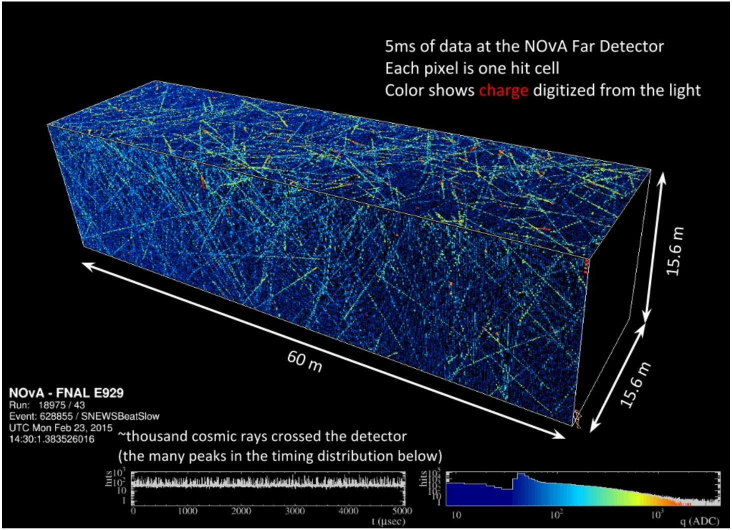
View of different event types





The Far Detector of NOvA

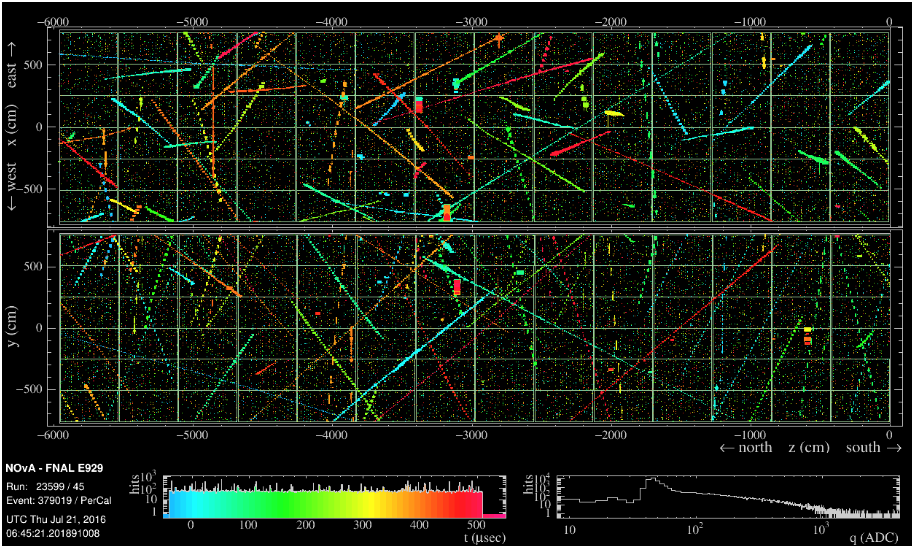
FD is located on the surface. Frequency of cosmic ray detections ∼100 kHz



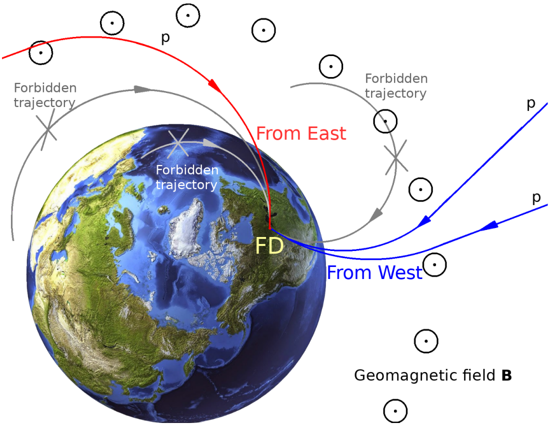
5ms of data at the NOvA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light

~thousand cosmic rays crossed the detector
(the many peaks in the timing distribution below)

Cosmic rays in the NOvA FD

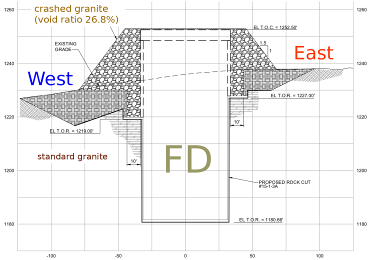


East-West Asymmetry



Asymmetry:

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



Only muons, stopping inside the FD, are used in this analysis. Energies of through-going muons are higher in general, and geomagnetic effect on them should be less marked.

Uncorrected flux asymmnetry

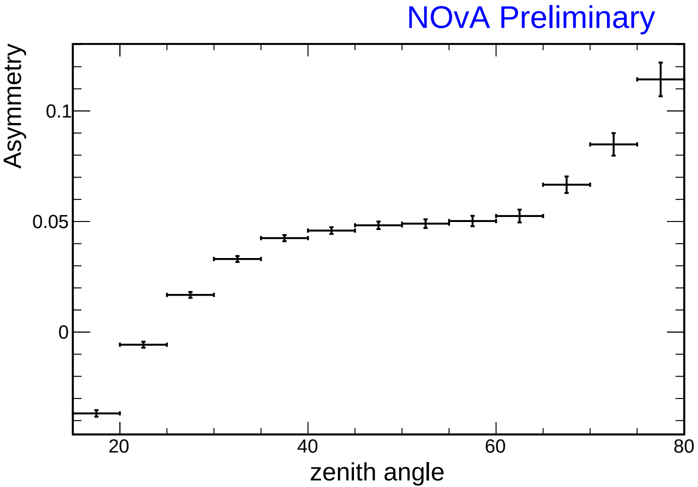
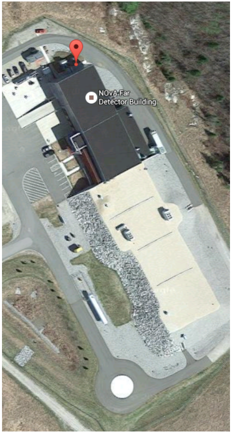
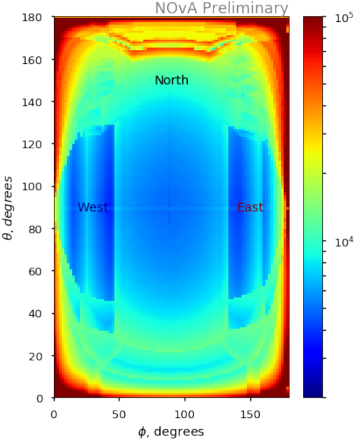


Figure: East-West asymmetry of stopping muons (uncorrected) vs. zenith angle

FD overburden is also asymmetrical

Google-map view of the FD site at Ash River, MN





Distribution of matter density $[g/cm^2]$ seen from the center of the FD

Attenuation factor

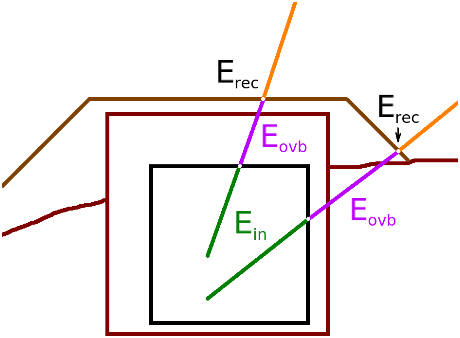
- We need to know 'real', not deformed, muon fluxes on the surface.
- So each track counted with weight equal to 1/efficiency (a function of track direction, the energy of muon in the moment of coming to the detector, etc) and its energy is recalculated.

The energy that stopped muon had on the surface:

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

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

E_{ovb} estimation based on overburden description $dE_\mu/dx = f(E_\mu)$



Energy reconstruction accuracy

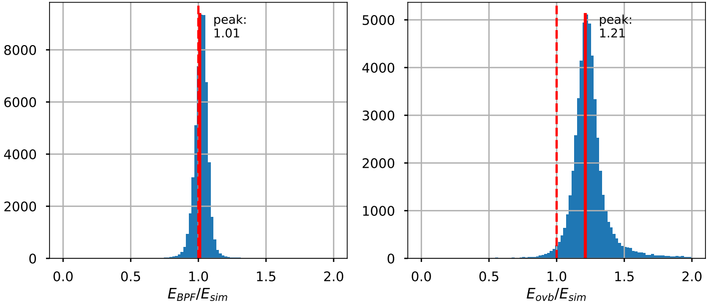
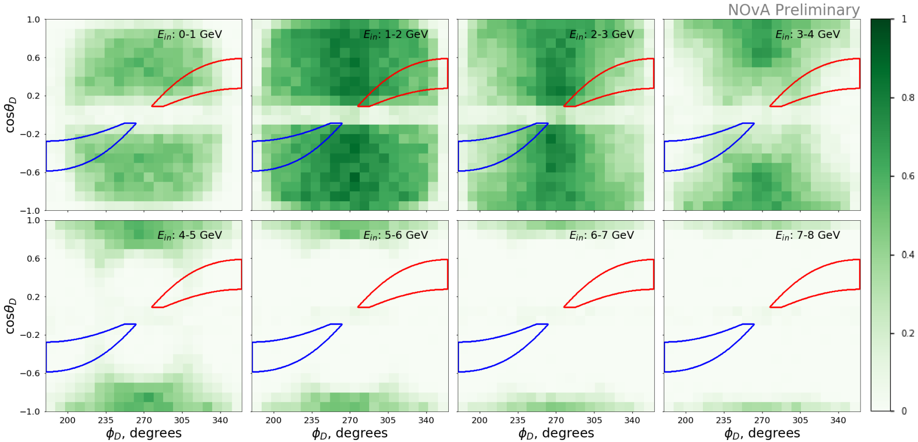


Figure: Relative resolution of stopping muon energy reconstruction: left - inner part, right - overburden part. Systematic error is to be understood

This is the other reason of why we look only on muons, stopping inside the FD: because their energy can be estimated by this method.

Reconstruction efficiency

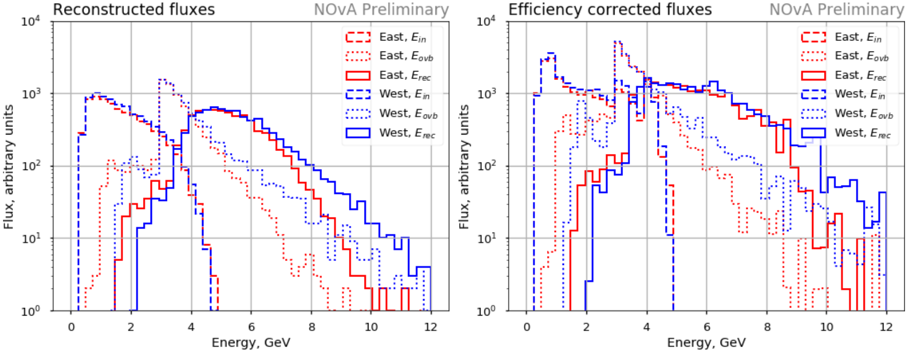
Counting only muons, stopping inside the fiducial volume



Areas of interest: fluxes coming from ($\pm 10^\circ$) the West and from the East

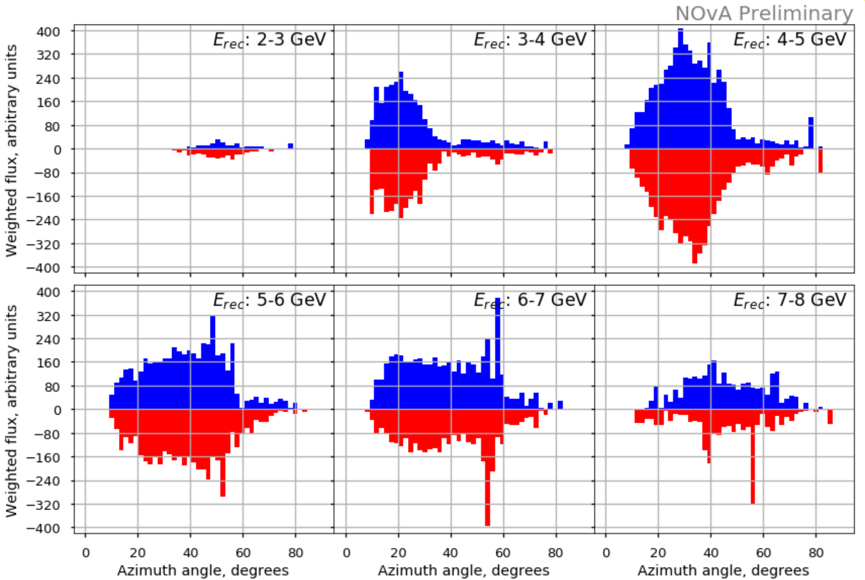
Energy spectra

Low energy part reduces muon flux due to overburden, high energy muons pass through the detector



Difference between West and East fluxes is clearly seen

Efficiency corrected fluxes vs. zenith angle

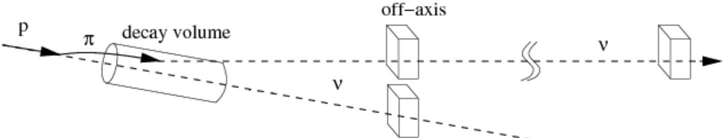


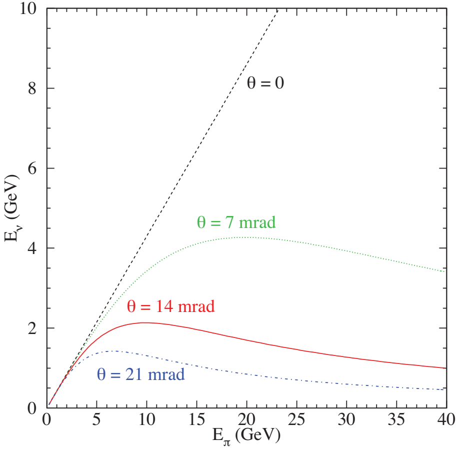
Summary and plans

- Current results show a good capability of the NOvA Far Detector to study the East-West asymmetry effect in the atmospheric muon flux
- We have reasonable statistics at $3 - 7$ GeV for the following analysis
- Further study includes choosing cuts on the muon energy and angles, estimation of statistical and systematic uncertainties of efficiency corrected fluxes, calculation of the East-West asymmetry and physical interpretation as well

Thank you!

Off-axis experiment idea

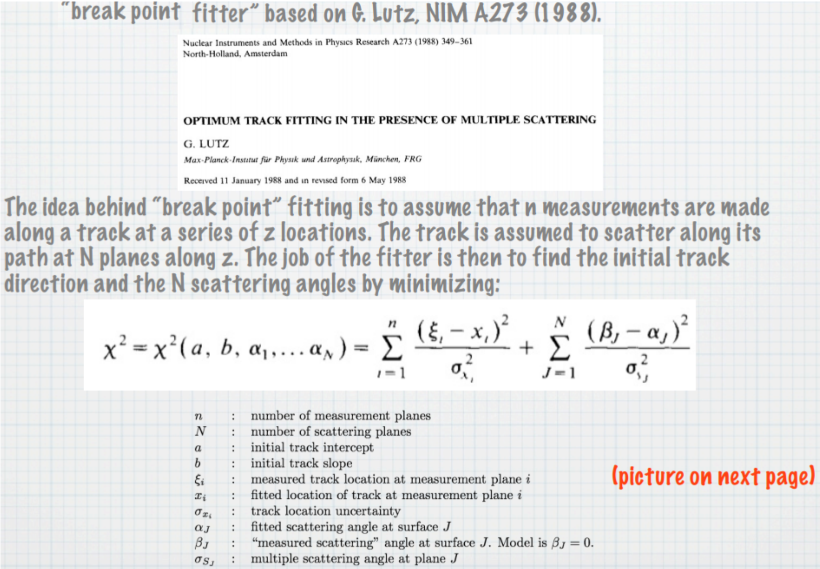




$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$\frac{dE_\nu}{dE_\pi} = \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{1-\gamma^2\theta^2}{\left(1+\gamma^2\theta^2\right)^2}$$

BreakPointFitter



"break point fitter" based on G. Lutz, NIM A273 (1988).

Nuclear Instruments and Methods in Physics Research A273 (1988) 349–361
North-Holland, Amsterdam

OPTIMUM TRACK FITTING IN THE PRESENCE OF MULTIPLE SCATTERING

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Received 11 January 1988 and in revised form 6 May 1988

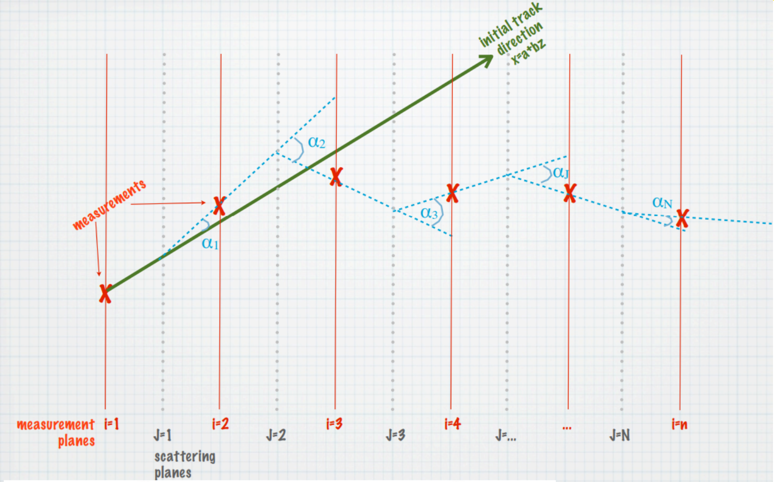
The idea behind "break point" fitting is to assume that n measurements are made along a track at a series of z locations. The track is assumed to scatter along its path at N planes along z. The job of the fitter is then to find the initial track direction and the N scattering angles by minimizing:

$$\chi^2 = \chi^2(a,\, b,\, \alpha_1, \ldots \alpha_N) = \sum_{i=1}^{n} \frac{(\xi_i - x_i)^2}{\sigma_{x_i}^2} + \sum_{J=1}^{N} \frac{(\beta_J - \alpha_J)^2}{\sigma_{S_J}^2}$$

n : number of measurement planes
N : number of scattering planes
a : initial track intercept
b : initial track slope
ξ_i : measured track location at measurement plane i
x_i : fitted location of track at measurement plane i
σ_{x_i} : track location uncertainty
α_J : fitted scattering angle at surface J
β_J : "measured scattering" angle at surface J. Model is $\beta_J = 0$.
σ_{S_J} : multiple scattering angle at plane J

(picture on next page)

BreakPointFitter



$$x_i = a + b z_i + \sum_{J=1}^{N} \alpha_J (z_i - Z_J)\Theta(z_i - Z_J) = a + b z_i + \sum_{J=1}^{N} \alpha_J \zeta_{z_i, J}.$$

scattering at upstream sites affect all downstream sites with proper correlations

$$\zeta_{z,J} = (z - Z_J)\Theta(z - Z_J)$$