$\bar{\nu}_\mu$ Charged Current Inclusive Cross Section Measurement with NOνA Near Detector

Shih-Kai Lin

Colorado State University

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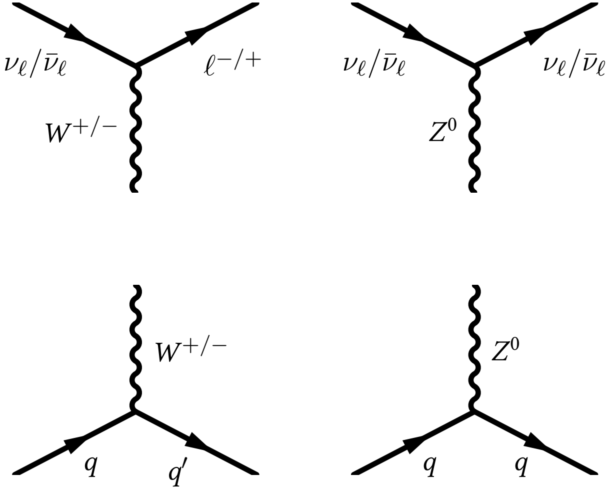
Why Cross Section Measurement

- essential in all neutrino experiments
- needed in the interpretation of neutrino oscillation data
- Historical measurements in the oscillation-relevant energy range, $E_\nu < 30$ GeV, have uncertainties of the order of 10%.
- Modern neutrino experiments make use of nuclear targets to increase event yields, which are less understood with nuclear effects.

Neutrino Interactions



charged current
flavor changing

neutral current
flavor conserving

Neutrino-Nucleon Charged Current Interactions

- quasi-elastic scattering: (target changes but no break up)

$$\nu_\mu + n \to \mu^- + p$$

- nuclear resonance production: (target goes to excited state, N^* or Δ)

$$\nu_\mu + n \to \mu^- + p + \pi^0$$
$$\nu_\mu + n \to \mu^- + n + \pi^+$$

- deep-inelastic scattering: (nucleon broken up)

$$\nu_\mu + quark \to \mu^- + quark'$$

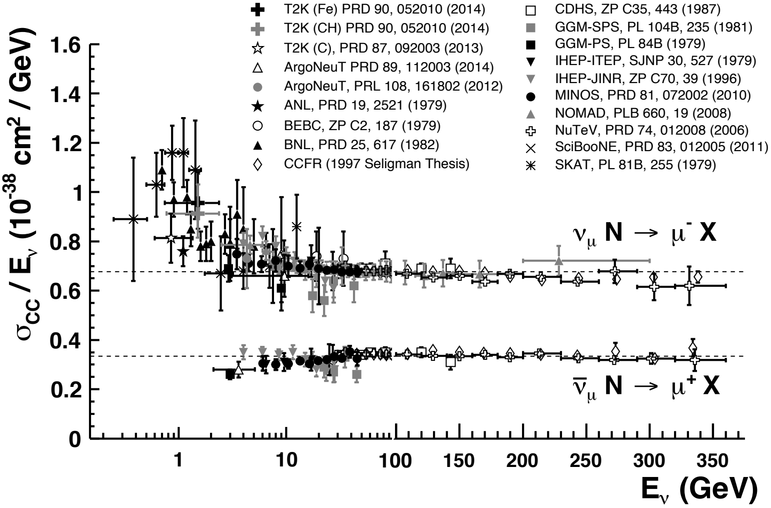
- "Inclusive" means all channels combined. Any event with an outgoing muon is included.

How to Measure Total Cross Section

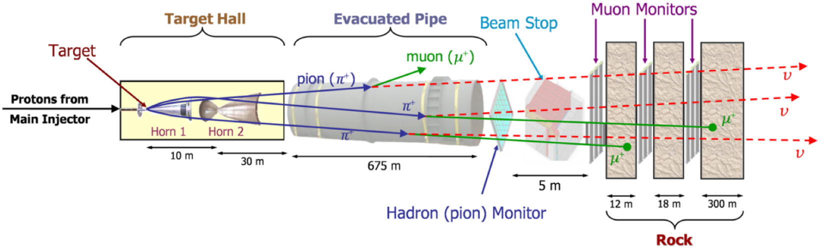
$$\sigma(E) = \frac{\left(N_s(E) - N_b(E)\right)/\epsilon(E)}{\phi(E) N_t}$$

, where
$\sigma(E)$ is the total cross section (cm^2),
$N_s(E)$ is the selected number of events,
$N_b(E)$ is the background number of events,
$\epsilon(E)$ is the selection efficiency,
$\phi(E)$ is the neutrino flux, and
N_t is the areal number density of the target nucleus (cm^{-2})

Measurements to Date

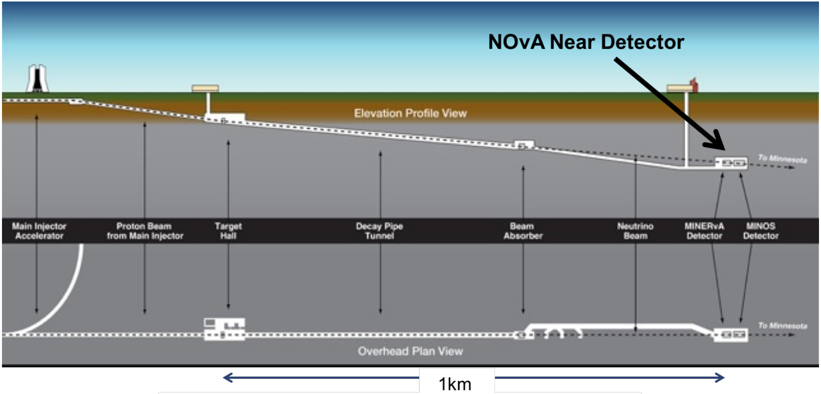


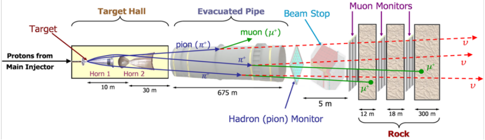
Where Do the Neutrinos Come From



- 120 GeV proton on carbon target, POT = Protons on Target
- Horn pulsed at -200 kA (or +200 kA to make anti-neutrino beam)
- Every 1.3 s we get 6 batches of protons from Booster on the target = 1 beam spill
- 10 μs of beam = 1 beam spill
- Every time we are going to get this 10 μs of beam the people at accelerator division sends us a signal letting us know.

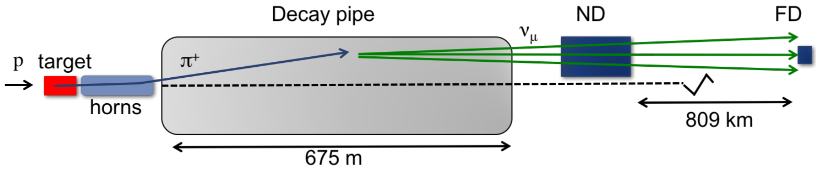
Near Detector Location

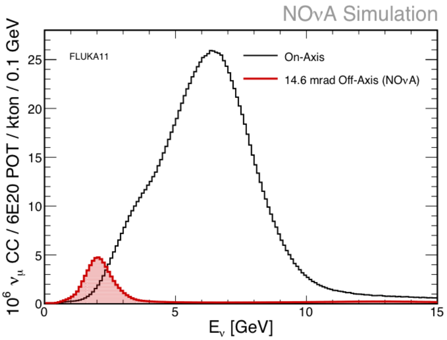




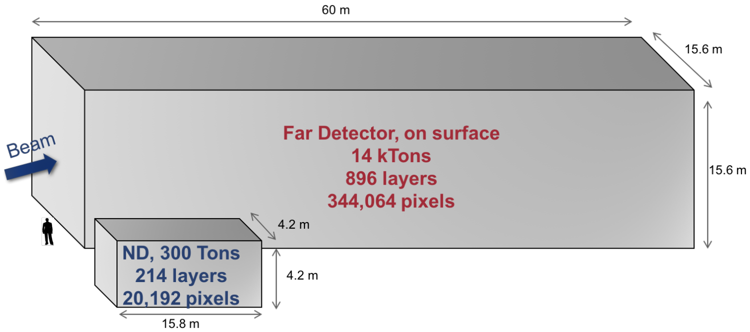
NOνA near detector is 1 km from the target 105 m underground.

NOνA Off-axis Beam



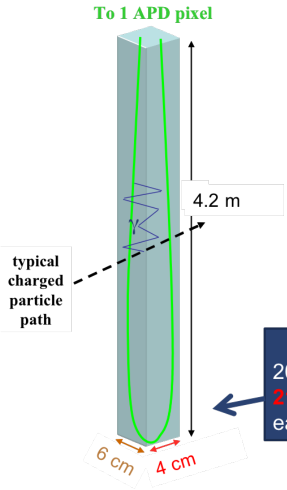


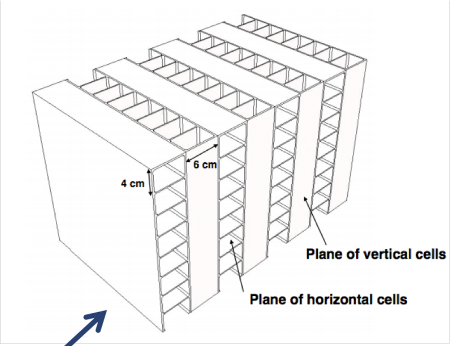
Detector Dimensions



Two functionally identical 65% active low-Z tracking calorimeters

Detector Cells





Near Detector
20,193 identical cells constructed into
214 alternating horizontal and vertical **planes**,
each plane of **96 cells** long*

*Except muon-range stack with 64 cells high

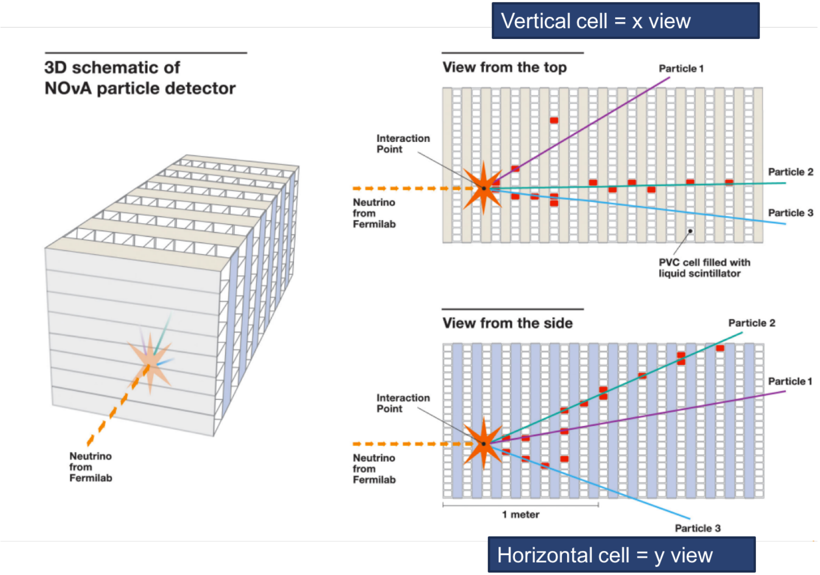
Cells constructed into horizontal and vertical planes for 3D reconstruction

NOνA Scintillator

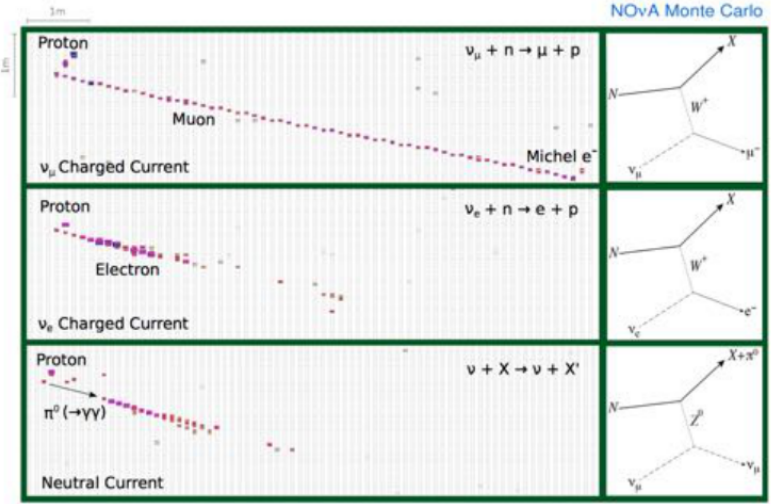
- material producing light when a charged particle travels through it
- by mass NOνA scintillator is mostly mineral oil solvent
- blended into the mineral oil are a primary scintillant to generate UV light and two wavelength shifters converting UV to blue light
- wavelength shifting fiber shifts blue to green light and guides the light to avalanche photodetectors
- light yield is modeled by the Birks-Chou model

$$\frac{dL}{dx} = \frac{L_0 \frac{dE}{dx}}{1 + k_B \frac{dE}{dx} + k_C \left(\frac{dE}{dx}\right)^2}$$

Event Schematic

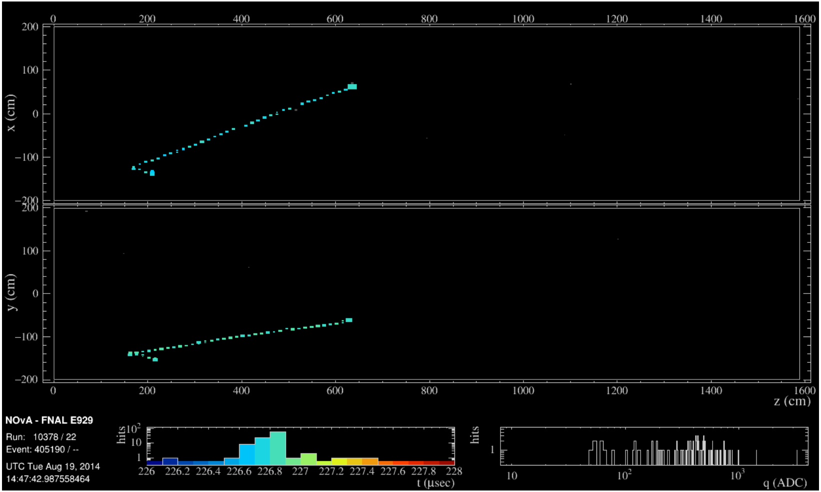


Neutrino Event Topology



1. the muon leaves a long minimum ionizing particle (MIP) track
2. the electron ionizes in the first few planes before starting a shower
3. the pion is a shower with a gap in the first few plane

ν_μ Charged Current Signal Event Display



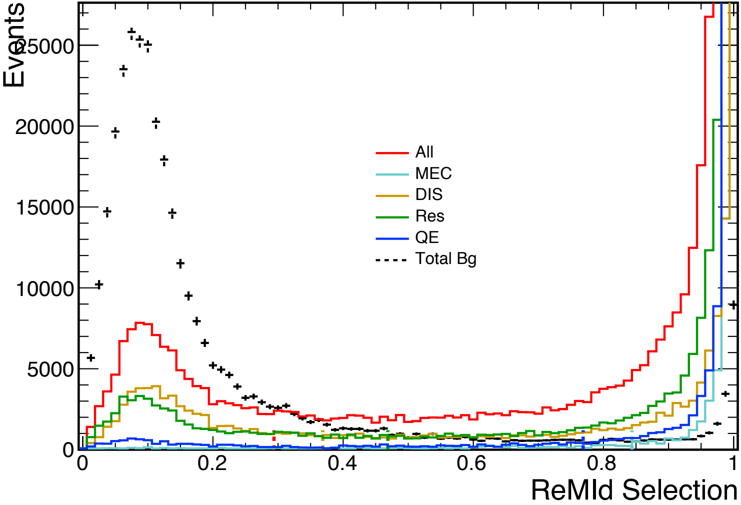
$\bar{\nu}_\mu$ Charged Current Event Selection

1. quality cut:
   requires a track to be reconstructed, removes low cell hits events, and removes vertical events, etc.
2. containment cut:
   requires the muon track to be contained in the detector
3. particle identification (PID):
   Where all tricks are.

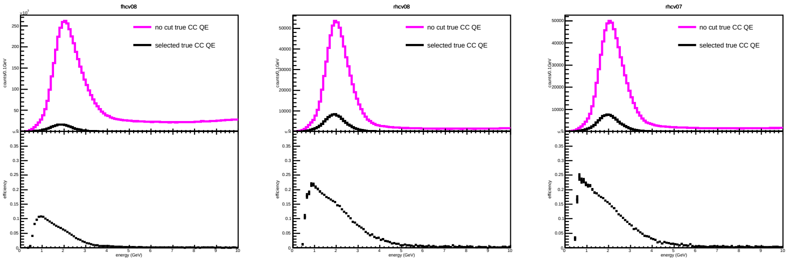
Reconstructed Muon Identification (ReMId)

- ReMId uses a k-Nearest Neighbors (kNN) algorithm to make its determination.
- input variables are
  - log-likelihoods using the $\frac{dE}{dx}$ of the track
  - log-likelihoods bases on the scattering observed in the track
  - the track length
  - the fraction of planes used to create the $\frac{dE}{dx}$ log-likelihood
- The kNN returns a value between 0 and 1, 1 being muon-like and 0 being background-like.
- A cut value is optimized to minimize the statistical error on the parameter interested.

ReMId Distributions for Different Modes



Event Selection on Monte Carlo



Cut used: Quality + Containment + ReMId

Items Contributing to the Uncertainties of Cross Section Measurement

- Geant4 nuclear model:
  particles from CC interactions undergo rescattering in the nuclei
- Birks parameter tuning:
  energy calibration
- energy scale:
  how well the neutrino energy is reconstructed
- flux uncertainties
- rock events:
  neutrino interactions outside of the detector entering the detector
- GENIE:
  neutrino event generator involving model dependencies

Thank you!