Nuclear Medium Effects in Antineutrino Induced Deep Inelastic Scattering for $< E_{\bar{\nu}_\mu} > \sim$ 6GeV at MINERνA

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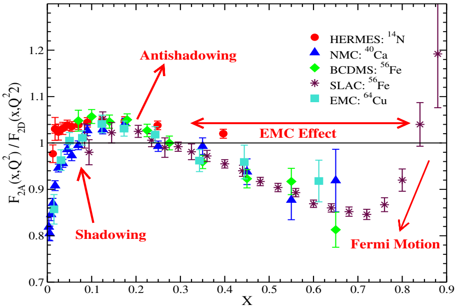
Motivation

Neutrino oscillation is one of the remarkable features and needs to be understood very well

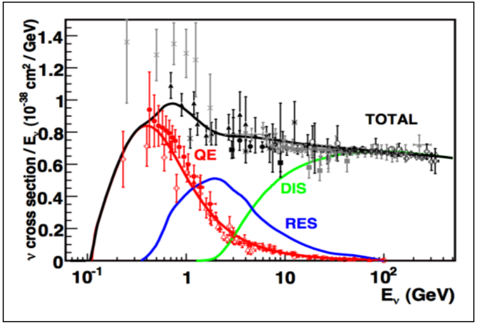
$$\boxed{\textbf{Event}} = \boxed{\phi(E_\nu)} \times \boxed{\sigma(E_\nu)} \times \boxed{N} \times \boxed{t} \times \boxed{P_{\nu_\mu \to \nu_e}}$$

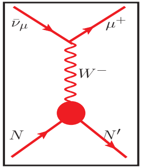
M. Sajjad Athar and S. K. Singh, The Physics of Neutrino Interactions (CUP, 2020)



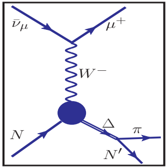
ν cross sections from different channels

Rev.Mod.Phys. 84 (2012) 1307-1341

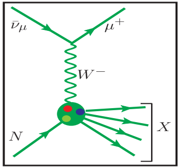




QE

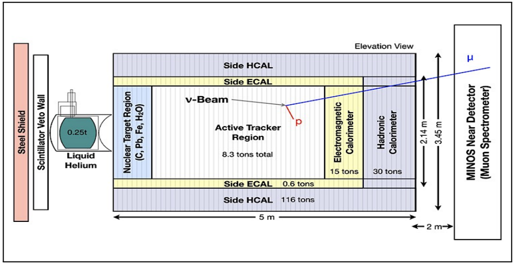


RES

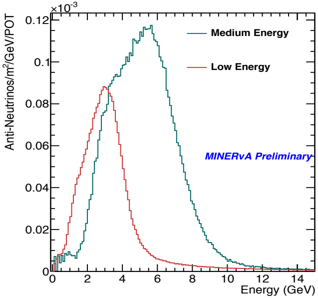


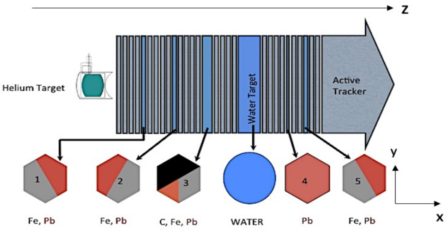
DIS

Elevation view



Located 100 meter underground, in front of MINOS detector.
Constructed of stack of hexagonal modules, supported on a frame along the beam axis

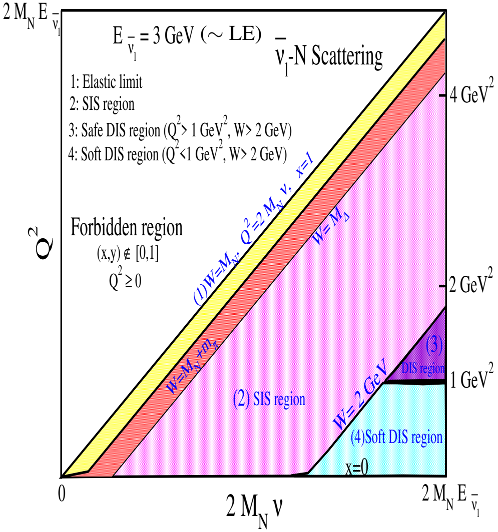




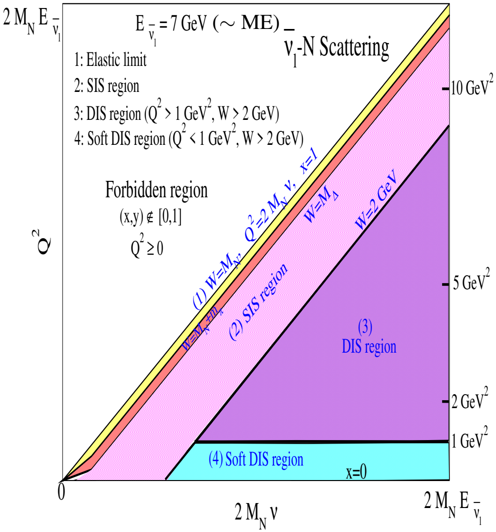
- High intensity $\nu_\mu/\bar{\nu}_\mu$ beam from NuMI beamline at Fermilab
- High statistics precision studies of $\nu-$A cross sections
- Passive nuclear targets: C, Fe, He, H_2O and Pb
- Active tracking region: Constructed of solid scintillator (CH)
- MINOS detector: muon spectrometer
- LE flux peaks $\sim$ 3.5 GeV and ME flux peaks $\sim$ 6 GeV

Kinematical Regions for $\bar{\nu}_l - N$ Scattering (DIS: $W \geq 2.0GeV$ and $Q^2 \geq 1GeV^2$)

- Hadronic center of mass energy: $W = \sqrt{M_N^2 + 2E_{had}M_N - Q^2}$.



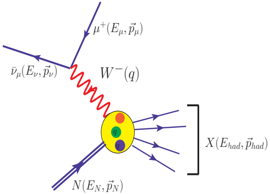
- Hadronic four momentum transfer squared: $Q^2 = -q^2 = 4E_{\bar{\nu}}E_\mu \sin^2\frac{\theta\mu}{2}$.



Analysis Goal

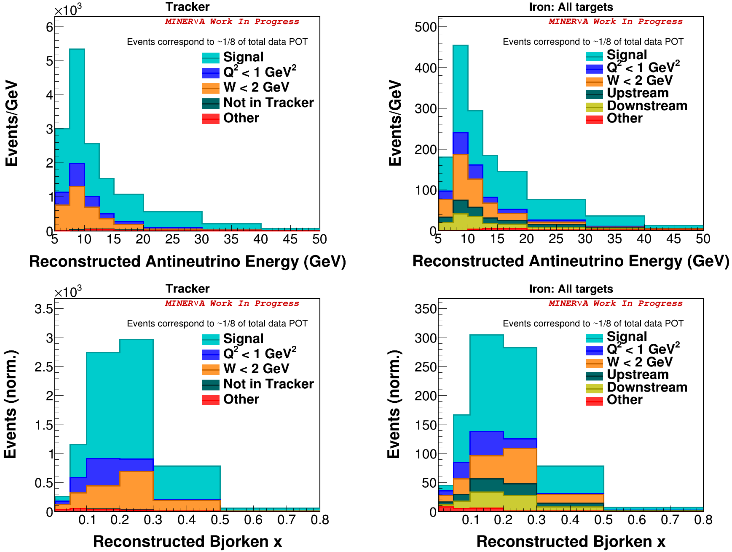
$$\bar{\nu}_\mu + A \rightarrow \mu^+ + X$$

- The aim is to extract the single differential cross sections for different nuclear targets (C, Fe and Pb) and to obtain the antineutrino cross section ratios of the passive nuclear targets (C, Fe, Pb) to the scintillator (CH) in the medium energy mode
- The energy of the incoming antineutrino: $E_{\bar{\nu}} = E_{had} + E_\mu$
- Bjorken variable "x" is the fraction of momentum carried by the struck parton $x = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2M_N E_{had}}$
- $\theta_\mu < 17^o$ and $2 < E_\mu < 50\ GeV$
- DIS events: $W > 2\ GeV$ and $Q^2 > 1\ GeV^2$



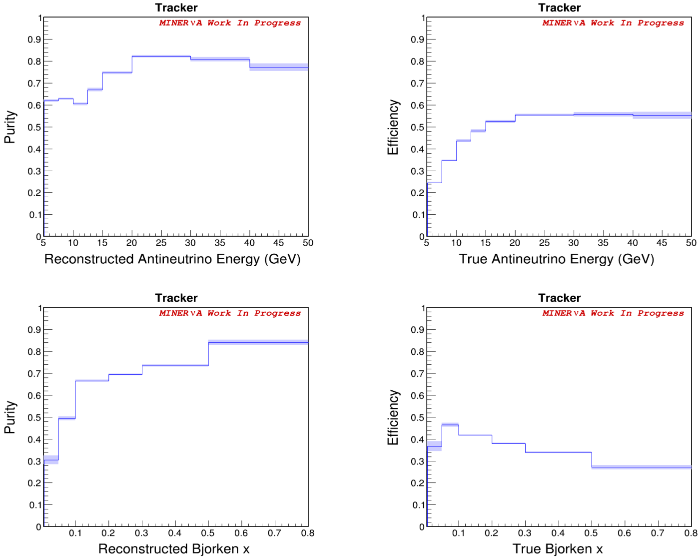
Event Selection and Background Categorization

- Physics background: Event that passes the DIS cuts because of imperfect detector resolution
- Plastic background: Scintillator events reconstructed in targets because of imperfect detector resolution
- **Iron:** Physics background events ($\sim 28\%$) and plastic background events ($\sim 17\%$) are the main backgrounds
- **Tracker:** Physics background $\sim 33\%$
- Other background: NC events + ν contamination ($\sim 1\%$)



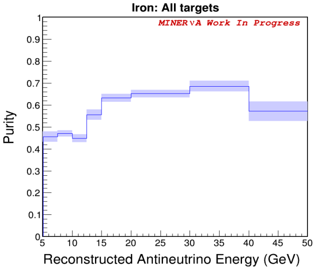
Purity and Efficiency in Tracker

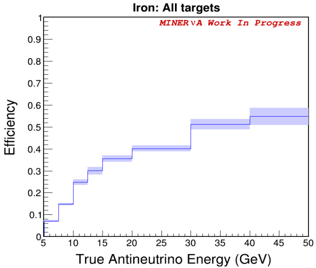
- Purity = signal/reconstructed events
- ML vertexing leads to better purity and efficiency
- **Purity** $\sim 66\%$
- Efficiency is the ratio of the events that passes both true as well as reco cuts to the events that passes only truth cuts
- **Efficiency** $\sim 38\%$

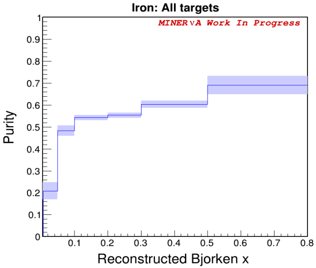


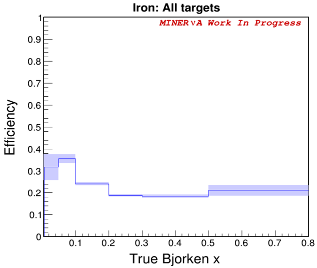
Purity and Efficiency in Iron

- Complex structure of passive target region lead to less purity and efficiency
- Each target is to be individually corrected by their respective efficiencies before the samples are combined by material
- **Purity** $\sim 53\%$
- **Efficiency** $\sim 21\%$



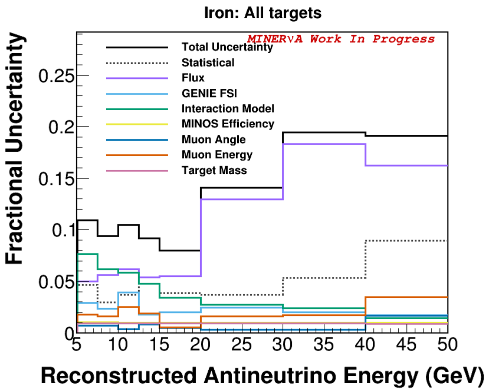


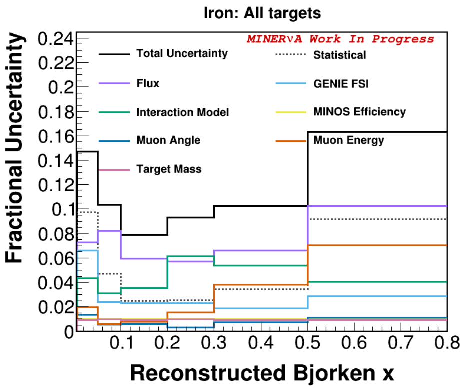




Systematic Uncertainties on Simulated Event Distributions

- Flux: $(\nu+\bar{\nu})$-electron scattering + inverse muon decay (IMD) medium energy flux constraint
- Most of the flux systematics will cancel out in cross-section ratios
- Statistical uncertainty will be reduced once we include additional POTs available
- Interaction model and muon reconstruction are also significant systematic uncertainties
- Hadronic energy systematic uncertainty is to be included





Conclusions and Next Steps

- Include the rest of the statistics available and add missing systematics
- Understand systematic uncertainties with unprecedented statistics collected
- Perform unfolding and extract cross-sections
- Exciting results are coming soon