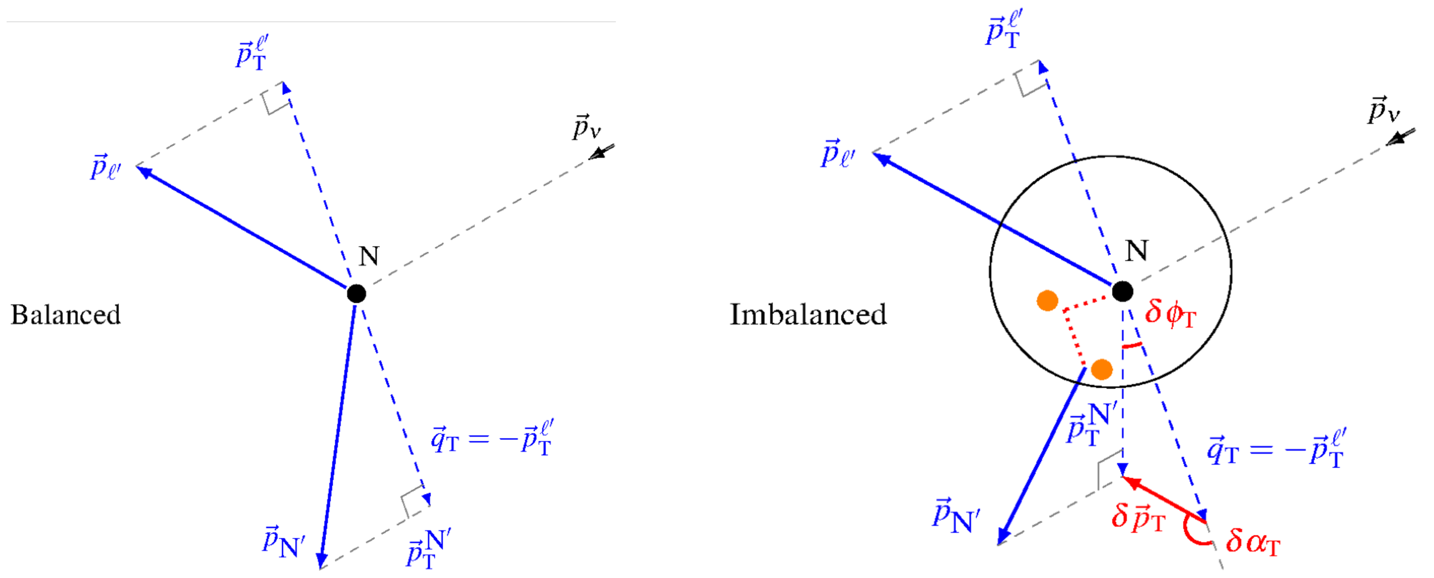
Measurement of Transverse Kinematic Imbalance in Neutrino-Nucleus Reactions at MINERvA

Deepika Jena for the MINERvA Collaboration, Fermi National Accelerator Laboratory

Introduction

In neutrino oscillation experiments better understanding of nuclear effects in neutrino-nucleus interactions is important.



In case of static nucleon target it is balanced as per momentum conservation – No nuclear effects

Complexity of nucleus: momentum-energy transfer bias the hadron kinematics. Any imbalance on the transverse plane is a manifestation of nuclear effects.

Transverse Kinematic Imbalances

- The initial and final state nuclear effects are probed using the momentum of the struck neutron and the direction of the *μ-p transverse momentum imbalance*.
- Convolution of Fermi motion and Intranuclear Momentum Transfer (IMT) due to FSI, resonance production, 2p2h etc.

$$\delta\vec{p}_T = \vec{p}_T^{N} - \Delta\vec{p}_T$$

Transverse $0 = \vec{p}_T^{\ell'} + \vec{p}_T^{N'} - \delta\vec{p}_T$

Longitudinal $E_\nu = p_L^{\ell'} + p_L^{N'} - \delta p_L$

New variable $p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$

The direction ($\delta\alpha_T$) of the *transverse momentum imbalance* is sensitive to IMT defined as:

$$\delta\alpha_T \equiv \arccos\frac{-\vec{p}_T^{\mu}\cdot\delta\vec{p}_T}{p_T^{\mu}\delta p_T}$$

MINERvA made measurements of these nuclear effects via

- the transverse kinematic imbalance between the charged lepton
- the primary final-state hadron in charged current quasi-elastic scattering.

References:

- T. Cai et al, Phys. Rev. D 101, 092001 (2020), arXiv:1919.08658
- X. Lu, et al. Phys. Rev. C94 (2016) No1, 015503
- X. Lu, et al. (MINERvA Collaboration) Phys. Rev. Lett. 121, 022504 (2018)
- A. Bodek and T. Cai, Eur. Phys. J. C79, 293 (2019), arXiv:1801.07975
- L.A Harewood et al, arXiv:1906.10576 [hep-ex]

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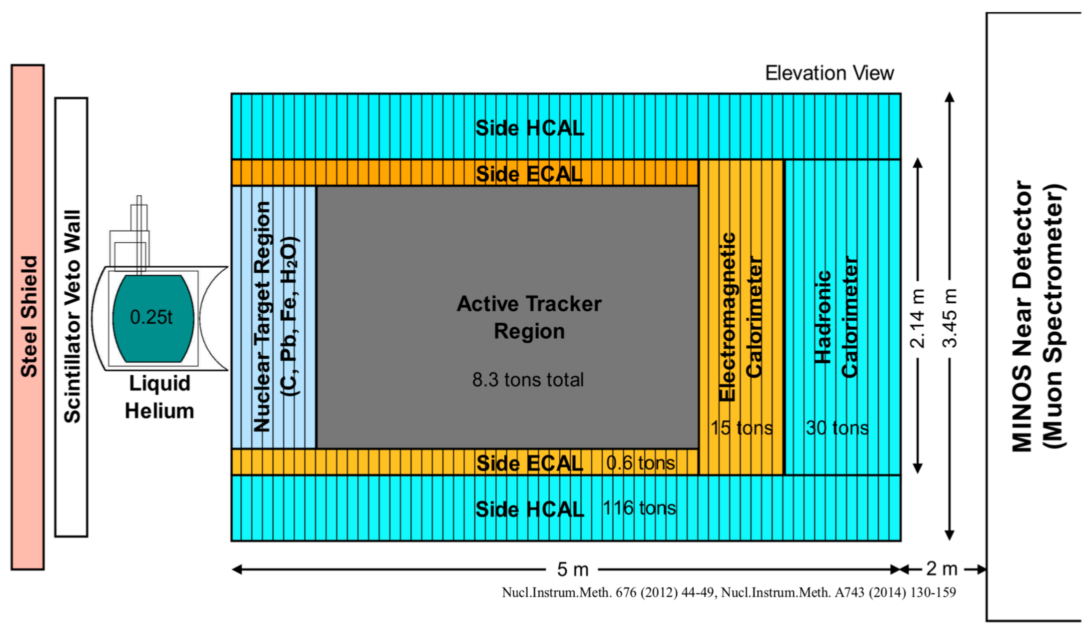
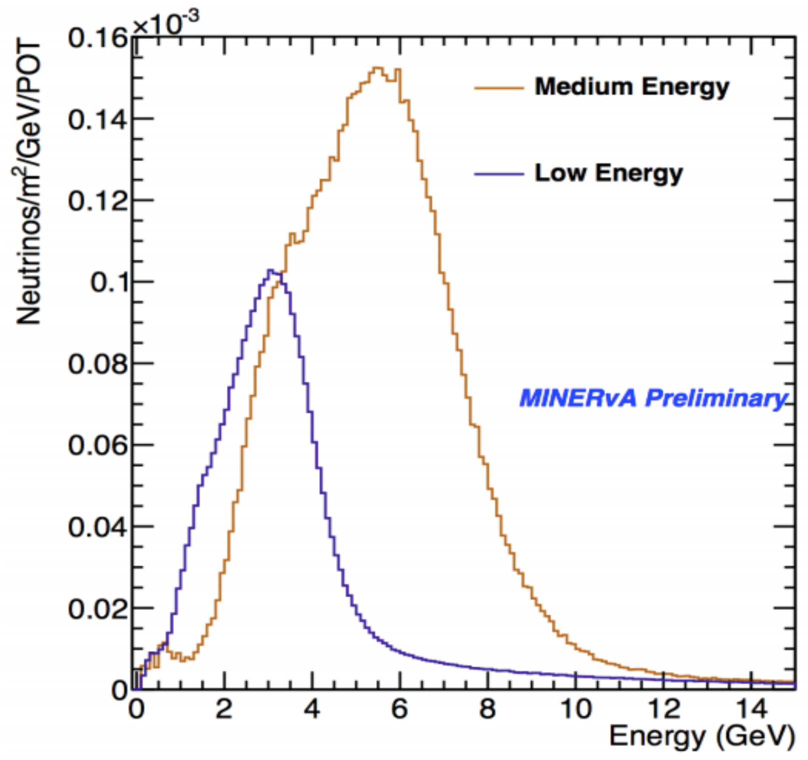
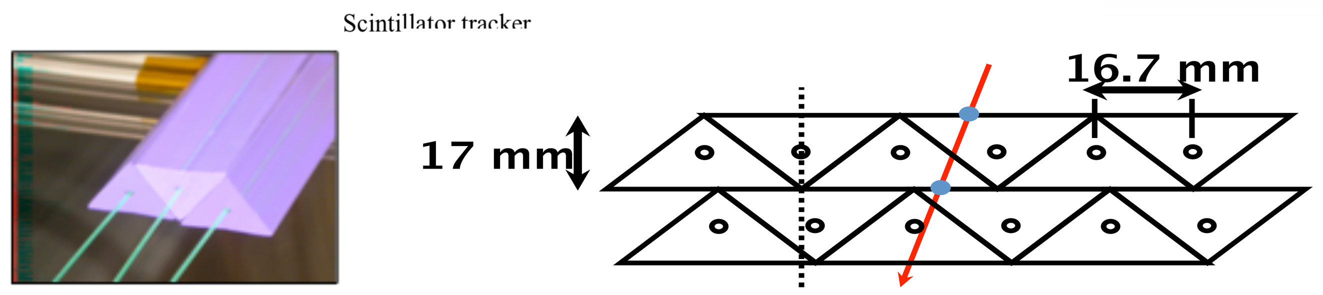
MINERvA Experiment





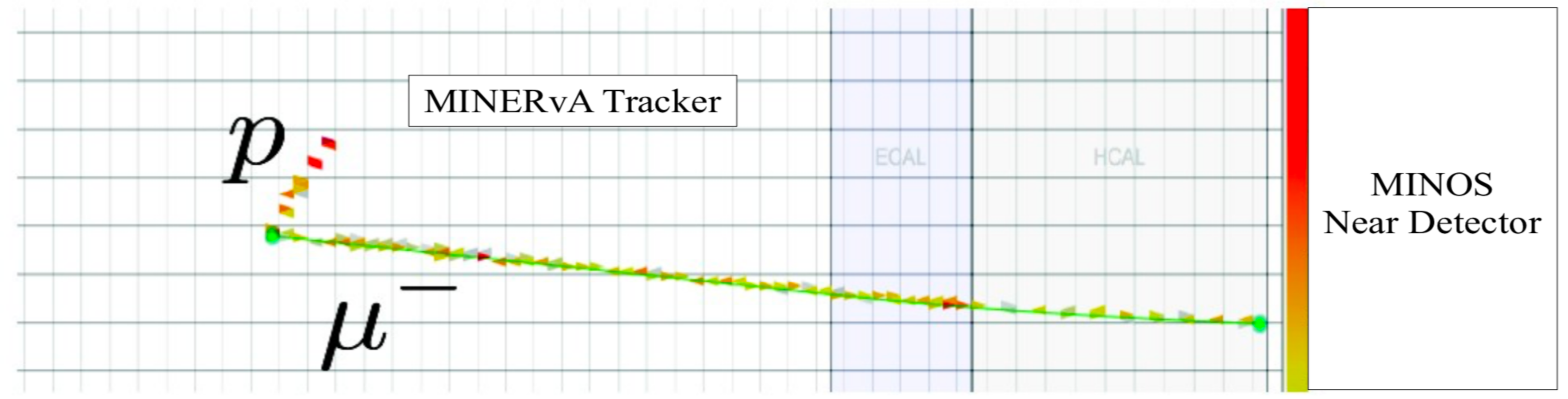


Fine-grained scintillator tracker surrounded by calorimeters

- MINERvA sits on-axis in the NuMI beam at Fermilab
- It uses MINOS near detector which serves as a magnetized muon spectrometer.
- Completed taking data both at low energy (*LE*) and medium energy (*ME*) run.
- The Low energy neutrino beam at $E_\nu \sim 3$ GeV accumulated: 3.28×10^{20} POT
  Medium energy neutrino beam $E_\nu \sim 6$ GeV accumulated: 10.61×10^{20} POT

Analysis Cuts

$\mu - p$ meson less production



- One muon candidate track matched to a MINOS track.
- At least one proton candidate (particle identification using dE/dx along the track)
- Phase-space selection for muon (p_μ, θ_μ) and proton (p_p, θ_p) momentum and polar angle :

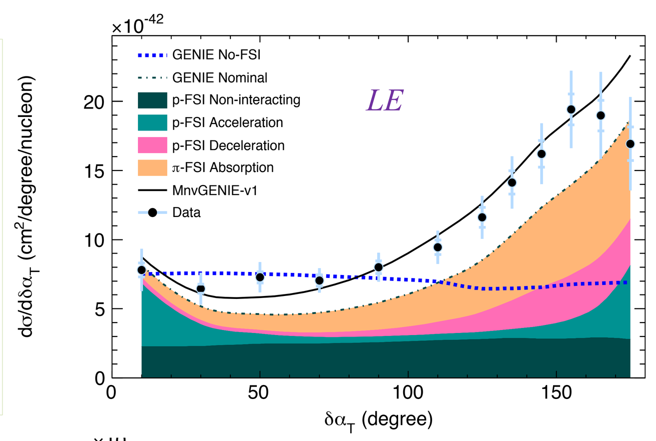
$$1.5\ \mathrm{GeV}/c < p_\mu < 10\ \mathrm{GeV}/c,\ \ \theta_\mu < 20^\circ$$
$$0.45\ \mathrm{GeV}/c < p_p < 1.2\ \mathrm{GeV}/c,\ \ \theta_p < 70^\circ$$

- Michel electron (from pion-muon-electron decay chain) tag to remove pion production.
- Simulation is done based on GENIE - MnvGENIE-v1 (elastic bug fix) includes RPA effect, the 2p2h Valencia model which has been tuned to MINERvA data and the non-resonant pion production prediction has been modified to agree with deuterium data.

Results and Discussion

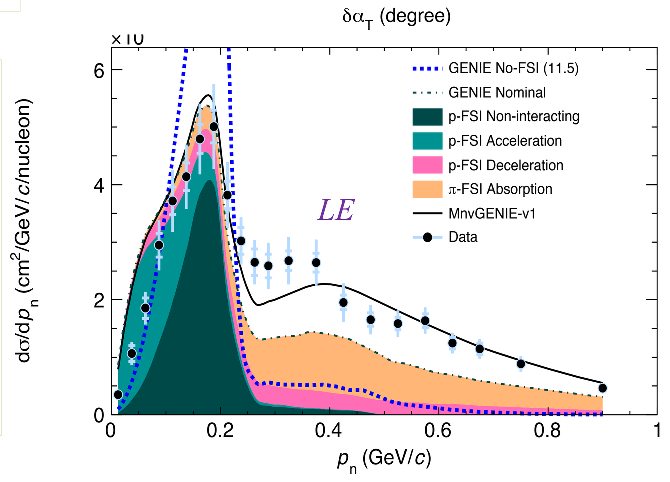
$|p_T^p| = |p_T^\mu|$

No nuclear effects. For the simulation without FSI, the distribution of $\delta\alpha_T$ is flat



$|p_T^p| < |p_T^\mu|$

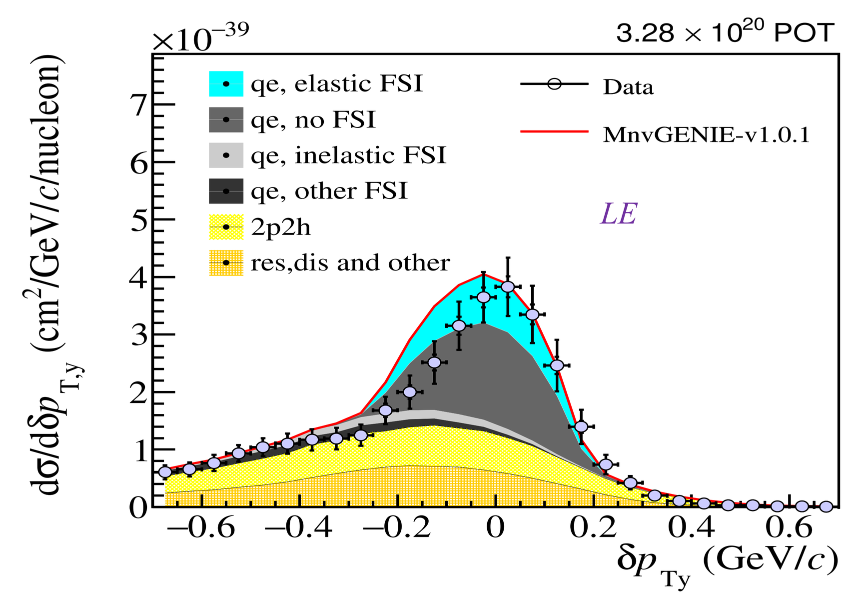
proton is decelerated by nuclear effects and effects of FSI are seen at $\delta\alpha_T > 90^\circ$



- The nominal GENIE prediction with decelerating proton FSI does not contribute greatly to the transverse forward boosting region $\delta\alpha_T < \sim 90^\circ$ where accelerating proton FSI are the dominating IMT.
- Such accelerating FSI are responsible for the QE peak distortion beyond 5-σ total uncertainty at the lowest p_n.
- The overall MnvGENIE-V1 describes data well.

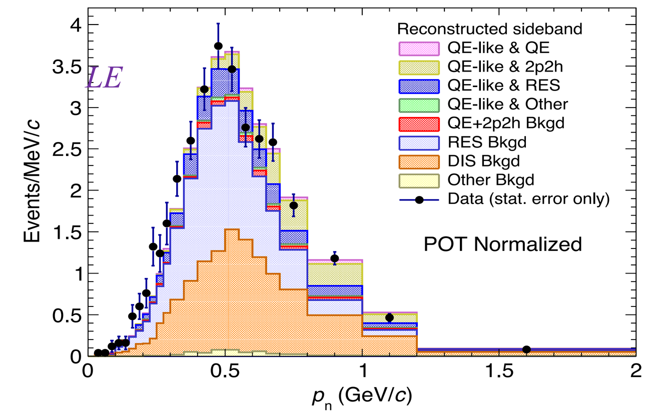
Transverse Binding energy:

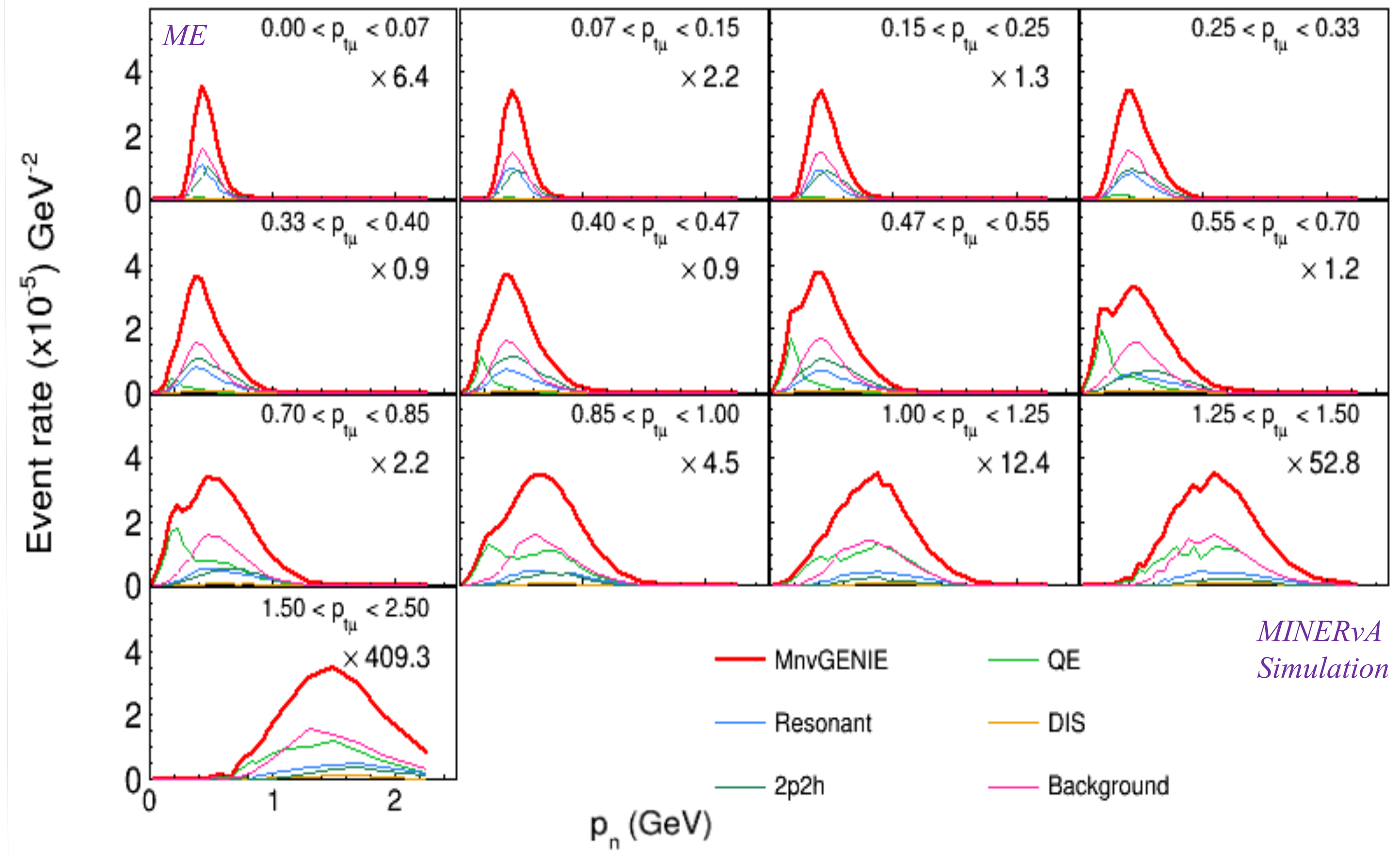
- The leptonic system provides energy to the hadronic side of the reactions to bring a bound nucleon on-shell and separate it from the remnant nucleus.
- Projection of transverse balance into the reaction plane is directly biased by energy required to remove nucleon from nucleus.



- δp_{Ty} is positive if the proton has gained momentum along transverse muon momentum direction
- A shift in the QE peak along the y-direction shows the sensitivity to the interaction energy.

- Ongoing: Along with making 1-D measurements, double differential cross-section of TKI variables as a function of p_μ are being studied at ME.
- QE peak distortion is observed in ME prediction.





Future medium energy MINERvA analysis with higher statistics will study these TKI variables and probe asymmetry in more detail.

Summary:

- The study of TKI helps to disentangle the nuclear effects in neutrino-nucleus interactions which is most relevant for oscillation measurements.
- Study of these variables will help to develop more accurate nuclear models with precision measurements and new techniques that disentangle the nuclear mess.
- Better modeling of the binding energy can reduce bias in neutrino energy reconstruction and these observables can be applied in current and future experiments to better constrain nuclear effects.