

# Theoretical predictions of transverse kinematic imbalance in neutrino-nucleus interactions

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Distributions of transverse kinematic imbalance in neutrino-nucleus interactions in the few GeV regime are sensitive to nuclear effects. We present a study comparing the latest predictions of transverse kinematic imbalance from the interaction simulations, NuWro and GENIE. We discuss the differences between the model predictions.

PRESENTED AT

NuPhys2015, Prospects in Neutrino Physics  
Barbican Centre, London, UK, December 16–18, 2015

## Introduction

Neutrino interaction models currently constitute a significant proportion of future few GeV neutrino experimental uncertainty budget. Conventionally, investigation has focused on how using nuclear targets affects the charged lepton kinematics—as opposed to interactions on free nucleon targets. Such effects can be conflated with unknown neutrino energy for neutrino beams produced by accelerators. Single-transverse kinematic imbalances exhibit a significantly reduced dependence on neutrino energy and data measurements will provide new insight into a number of nuclear effects [1, 2]. The double-transverse kinematic imbalance,  $\delta p_{\text{TT}}$  provides a novel method of reconstructing neutrino energy spectra independent of nuclear effects [3, 4]. The definitions of the single-transverse variables  $\delta p_{\text{T}}$ ,  $\delta\phi_{\text{T}}$ ,  $\delta\alpha_{\text{T}}$ , as well as  $\delta p_{\text{TT}}$  are shown in Figure 1.

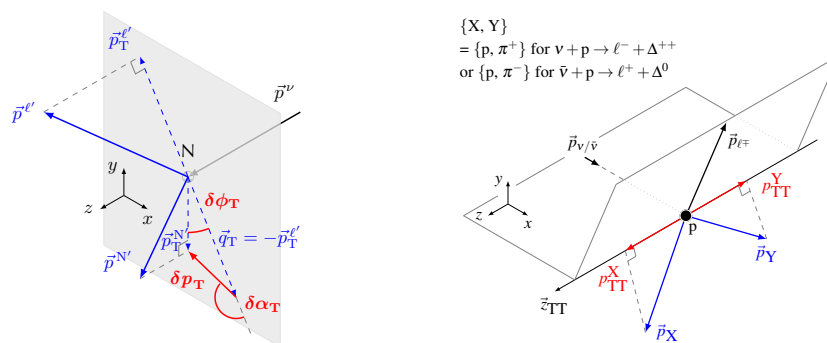


Figure 1: Single- (left) and double- (right) transverse kinematics. The variables  $\delta p_{\text{T}}$ ,  $\delta\alpha_{\text{T}}$ ,  $\delta\phi_{\text{T}}$ , and  $\delta p_{\text{TT}} \equiv p_{\text{TT}}^X + p_{\text{TT}}^Y$  each represents a departure from the kinematics of elementary neutrino interactions on stationary, free nucleons. Figures taken from [1, 4].

The following predictions are generated using GENIE 2.10.0 [5] with the nominal hA FSI model, and NuWro 11q [6]. The predicted distributions are generated using the NuMI on-axis  $\nu_{\mu}$  and  $\bar{\nu}_{\mu}$  flux shapes.

### Single transverse kinematic imbalance in neutrino quasi-elastic scattering

The observable  $\delta\phi_{\text{T}}$  characterises how ‘back-to-back’ the transverse components of the final states are. In the absence of FSI and multi-nucleon correlations, the only source of transverse kinematic imbalance should be the transverse component of the Fermi motion of the struck nucleon. This distribution has been measured in neutrino scattering before [7, 8, 9], most recently by the MINER $\nu$ A collaboration which presents a measurement of  $\varphi = 180^\circ - \delta\phi_{\text{T}}$  compared to a GENIE simulation. MINER $\nu$ A found a good agreement between the data and the GENIE simulation\*. The predictions from NuWro and GENIE are shown in Figure 2. The left panel shows that

\*The version of GENIE used, 2.6.2, did not contain an elastic FSI component

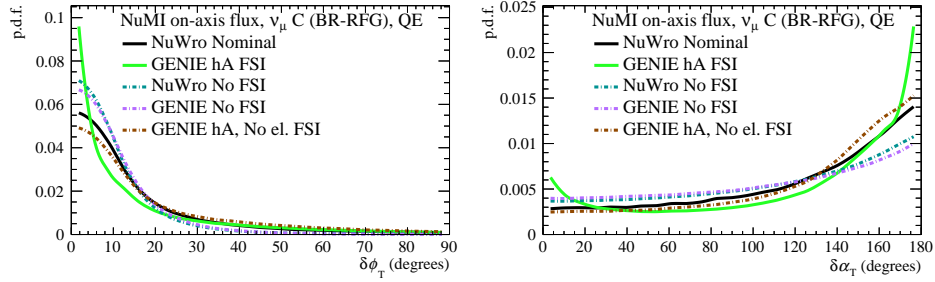


Figure 2: The NuWro and GENIE predictions for  $\delta\phi_T$  (left) and  $\delta\alpha_T$  (right). Nominal distributions are compared to the cases where FSI is disabled. Further comparison is made by removing nominal GENIE events that experienced proton elastic FSI (see text for exact definition).

the nominal GENIE simulation predicts a very sharp back-to-back peak. The most striking feature is that the enhancement with respect to the NuWro prediction around  $\delta\phi_T = 0$  is not evident in the GENIE ‘No FSI’ curve. The full simulation appears to induce less transverse imbalance than the case with hadronic re-interactions disabled.

The ‘transverse boosting angle’,  $\delta\alpha_T$ , shows the apparent ‘acceleration’ or ‘deceleration’ of the hadronic final state arising from nuclear effects. For  $\delta\alpha_T > 90^\circ$ ,  $\delta p_T$  points in a similar direction as the charged lepton—the hadronic final state has less transverse momentum than is expected from the free nucleon target case. The effect of intra-nuclear re-interactions is expected to be an energy-momentum transfer to the nuclear medium—a deceleration of the interacting hadronic state—which corresponds to a peak at  $\delta\alpha_T \sim 180^\circ$ . While both NuWro and GENIE predict this behaviour, as shown in Figure 2 (right), the GENIE prediction exhibits a significantly sharper deceleration peak and a less prominent peak at  $\delta\alpha_T \sim 0$  that corresponds to some accelerating effect. It is useful to investigate transverse imbalance as a function of the

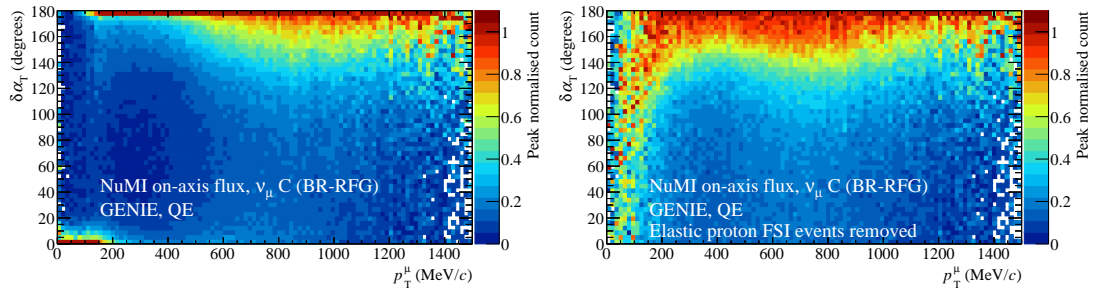


Figure 3: The variation of  $\delta\alpha_T$  with  $p_T^\ell$  for QE events, as predicted by GENIE, with (left) and without (right) elastic proton FSI.

charged lepton transverse momentum<sup>†</sup>. Figure 3 shows the GENIE  $\delta\alpha_T$  distribution

<sup>†</sup>This separates extra neutrino energy dependence caused by the  $p_T^\ell$  dependence of  $\delta\phi_T$  [1, 2]

in slices of lepton transverse momentum. Each  $p_T^\ell$  slice is normalised such that the most probable value is set to unity. The left panel shows that the accelerating peak in the  $\delta\alpha_T$  prediction is only evident at low  $p_T^\ell$ .

As suggested by the GENIE collaboration, we investigated removing events which include a final state proton that underwent an elastic interaction defined in the hA FSI model. The nominal GENIE simulation predicts that such events amount to about 40% of QE interactions at the NuMI beam energy. Having removed such events, both the  $\delta\phi_T$  and  $\delta\alpha_T$  distributions are more similar to the NuWro prediction (Figure 2). The sharp peaks in  $\delta\phi_T$  and  $\delta\alpha_T$  are notably reduced. The right panel of Figure 3 shows  $\delta\alpha_T$  as a function of  $p_T^\ell$  with elastic FSI events removed. The GENIE hA elastic FSI model causes proton final state acceleration for low  $p_T^\ell$  and strong deceleration for  $p_T^\ell \gtrsim 200$  MeV/c. The resulting sharp peaks at  $\delta\phi_T = 0$  and  $\delta\alpha_T = 0, 180$  degrees indicate a ( $q_T$ -dependent<sup>‡</sup>) strong collinear enhancement in the proton intra-nuclear scattering cross section.

### Transverse kinematic imbalance in neutrino-induced resonance production

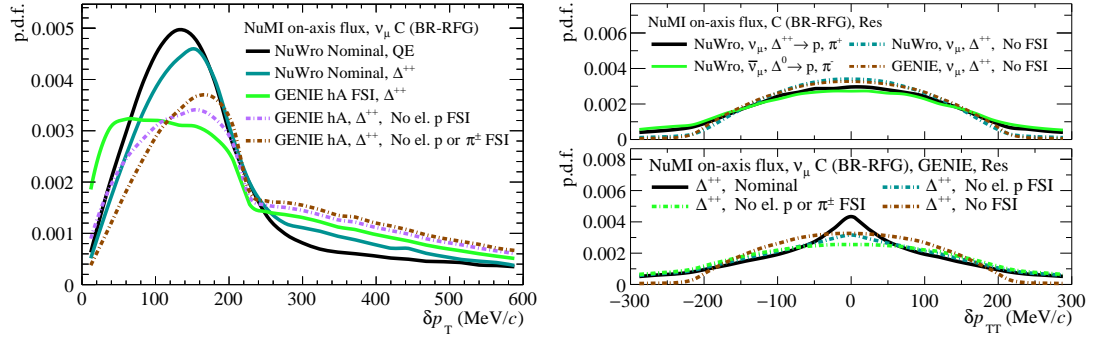


Figure 4: The NuWro and GENIE predictions for  $\delta p_T$  (left) and  $\delta p_{TT}$  (right). The features shown in the lower right panel are also exhibited in the  $p\pi^-$  and  $p\pi^0$  channels.

In resonance production, where the intermediate resonant state decays within the nucleus to multiple hadrons, nuclear effects change the kinematics of all hadronic final states. Details of such effects can be studied in  $p\pi$  channels as follows and provide new insight that is not accessible in QE interactions.

With reference to Figure 1,  $\vec{p}^{N'}$  becomes  $\vec{p}^{\text{RES}} = \vec{p}^p + \vec{p}^\pi$ . This opens up three new event selections,  $\nu_\ell + p \xrightarrow{\Delta^{++}} p + \pi^+ + \ell^-$ ,  $\nu_\ell + n \xrightarrow{\Delta^+} p + \pi^0 + \ell^-$ , and  $\bar{\nu}_\ell + p \xrightarrow{\Delta^0} p + \pi^- + \ell^+$ . The  $\delta p_T$  predictions for QE and  $\Delta^{++}$  production are shown in Figure 4 (left). The shape difference evident in the GENIE prediction shows that the effects of the elastic FSI component are not confined to nucleon FSIs but also exist for pions

<sup>‡</sup>See Figure 1 (left) for definition of  $q_T$ .

as well. Because the same model (BR-RFG [5, 6]) is used for the nuclear state in all simulations, a stronger FSI in GENIE can be inferred by its higher proportion of events with  $\delta p_T \gtrsim 250 \text{ MeV}/c$ .

Figure 4 (right) shows the GENIE and NuWro predictions for  $\delta p_{TT}$ . The top panel shows that without FSI both are consistent, and that the NuWro distribution widens as re-scattering takes place when FSI is enabled. The bottom panel shows the effect of the GENIE elastic component. Elastic re-interactions, in both nucleon and pion FSI of the hA model, result in an enhancement around  $\delta p_{TT} = 0$ .

## Summary and Outlook

The GENIE and NuWro predictions for a number of transverse kinematic imbalances have been shown. The phenomenological predictions exhibit significant shape differences in important regions of the distributions. Measurements of these observables are underway and should offer separation power among models of nuclear effects. A better understanding of the hadronic cascade, constrained by data measurement, will result in reduced systematic uncertainty for future neutrino cross-section and oscillation measurements.

## ACKNOWLEDGEMENTS

We express our gratitude to the NuWro Collaboration and the GENIE Collaboration, as well as to S. Dytman, Y. Hayato, K. McFarland and C. Wilkinson, for helpful discussions and suggestions.

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