Exploration of the beam profile using the ND280 detector in the T2K experiment

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on behalf of the T2K collaboration

Introduction

The T2K experiment (Fig. 1) studies neutrino properties by observing the effects of neutrino oscillations over long distances.

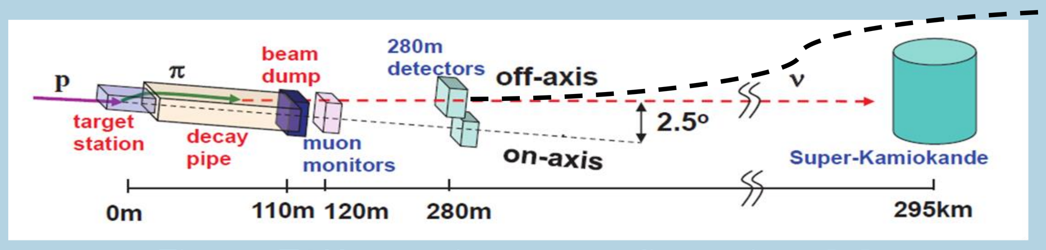


Fig. 1: T2K experiment configuration. [1]

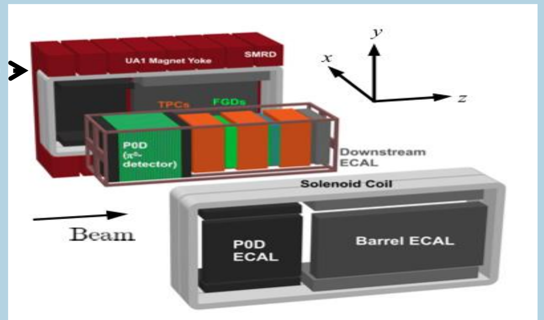


Fig. 2: The ND280 near detector. [2]

T2K has near a detector (ND280 in Fig. 2). Its purpose is to constrain neutrino beam properties such as flux and energy spectrum and to control systematic uncertainties.

Neutrino production steps:

- Accelerated protons hit a graphite target.
- These collisions produce secondary particles such as pions and kaons.
- Magnetic horns focus the secondary particles (current increased from 250kA to 320kA) + upgrade plans towards 1.3 MW beam (as discussed in Tetsuro Sekiguchi talk).
- Pions and kaons decay into neutrinos.

Reasons to place the Near and Far Detectors off-axis (2.5˚):

- Reduces dependence on parent particle energy.
- Achieves a narrower neutrino energy spectrum (Fig. 3).

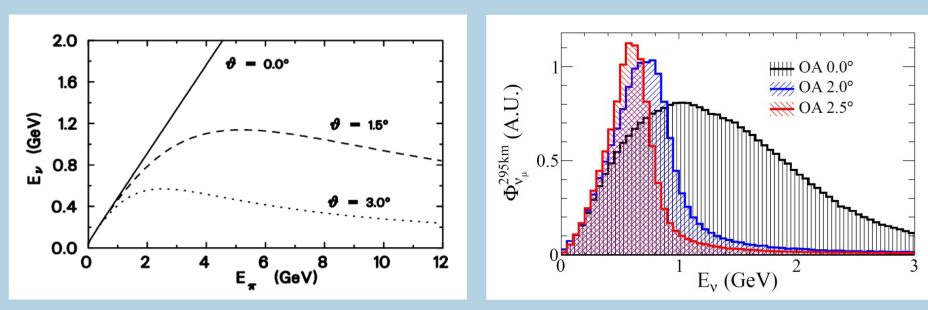


Fig. 3: Neutrino energy from pion decay as a function of pion energy (left) [2] and neutrino fluxes for different off-axis angles (right). [3]

Pions and kaons decay along a 96 m long decay volume.

Neutrino production location affects the off-axis angle at which the neutrino arrives at the near detector, which in turn **affects the observed neutrino energy spectrum**.

Methodology

We propose a **new experimental observable** to explore the decay position of parent particles:

- The neutrino direction is reconstructed using muon and proton tracks in CC0π1p events, where neutrino interacts in FGD1, and the muon and proton enter the TPC2 (Fig. 4).

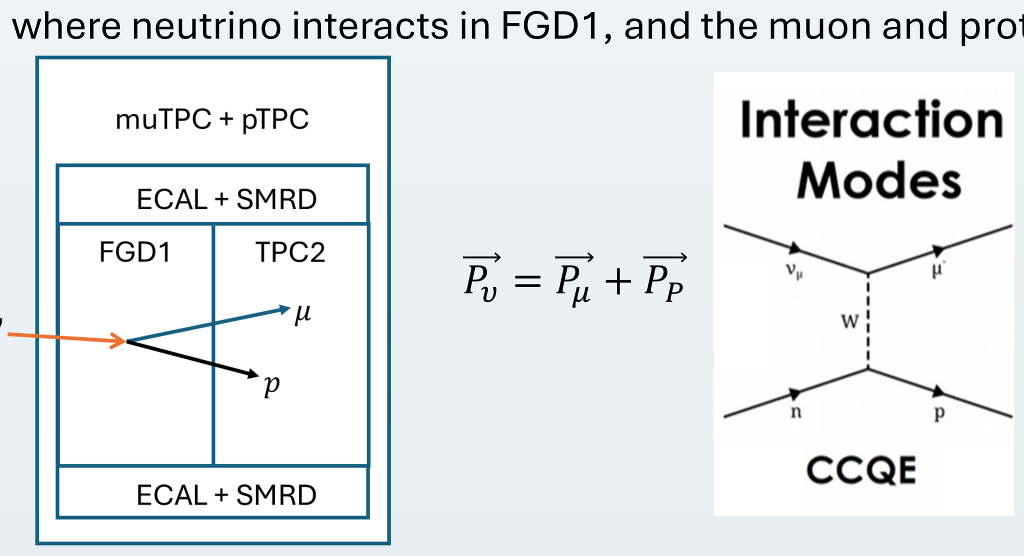


Fig. 4: The selection for neutrino interactions used in the analysis (left), and the Feynman diagram of the dominant interaction mode CCQE (right).

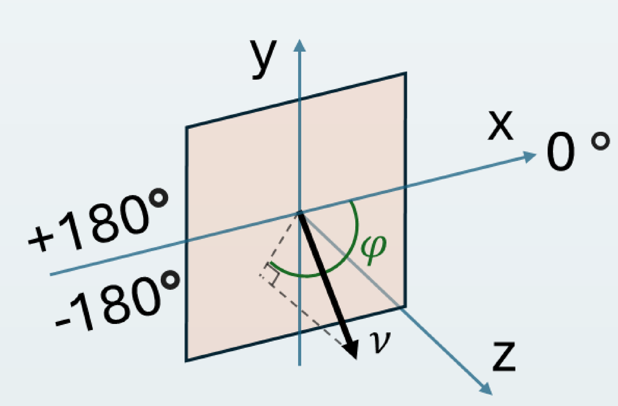
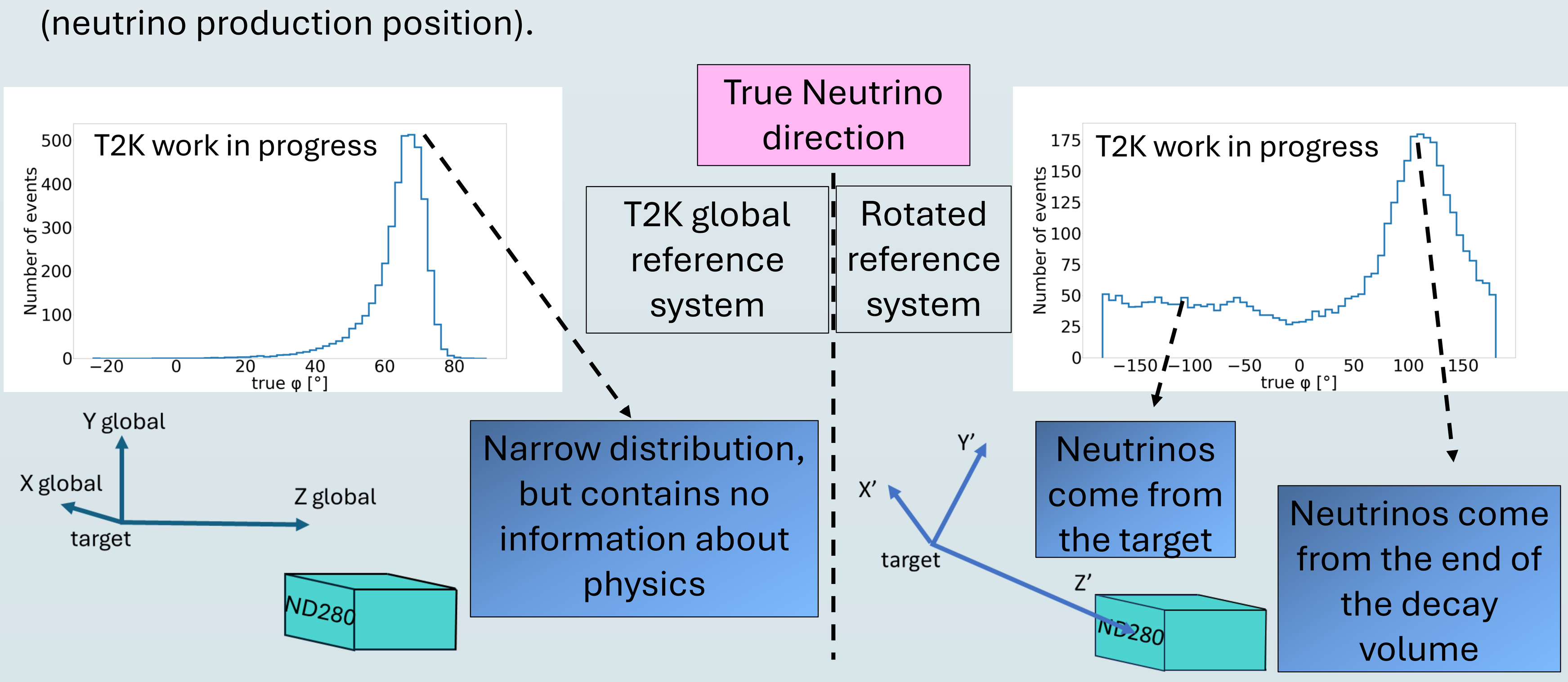


Fig. 5: The angle between the projection of the reconstructed neutrino vector onto the XY plane and positive X-axis.

- No additional phase space cuts were applied, but to reconstruct outgoing particles, momenta still need to be >400MeV/c (protons) and >250MeV/c (muons) with both having scattering angle θ with respect to the neutrino direction <90°.
- The neutrino direction is monitored by the azimuthal φ angle (Fig. 5).
- The global frame of reference is rotated to enhance the sensitivity to the neutrino direction (neutrino production position).



- 10 rotated reference frames are introduced (instead of 1).

Frames are evenly distributed between the beginning of the target and the beam dump, with each Z axis pointing towards the centre of the near detector (Fig. 6).

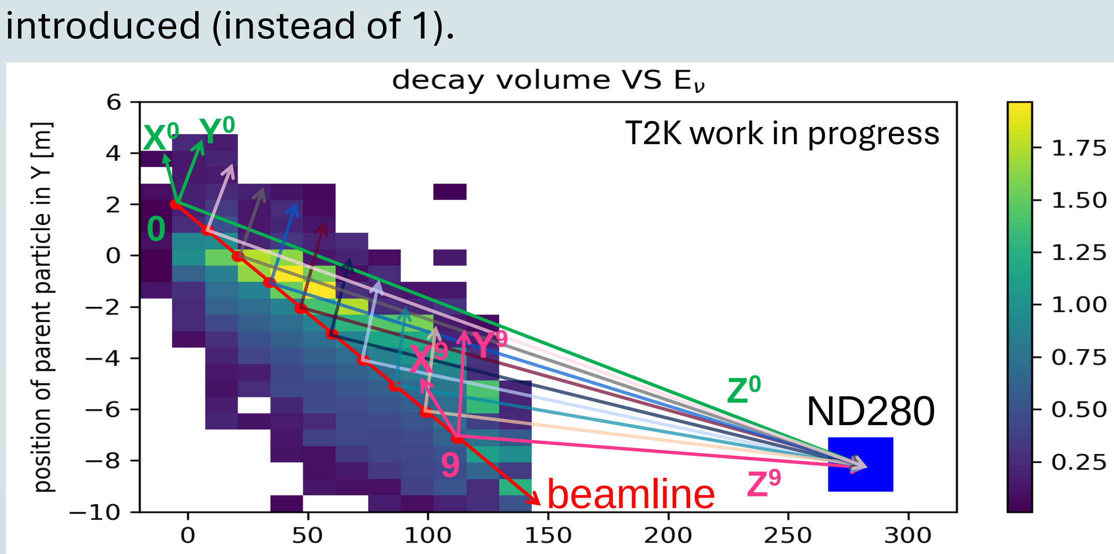


Fig. 6: The representation of the parent particle decay positions in the Y,Z axes with respect to the ND280 detector.

- With new frames of references, it is possible to determine from the reconstructed neutrino direction whether neutrino was produced before or after the given frame of reference.

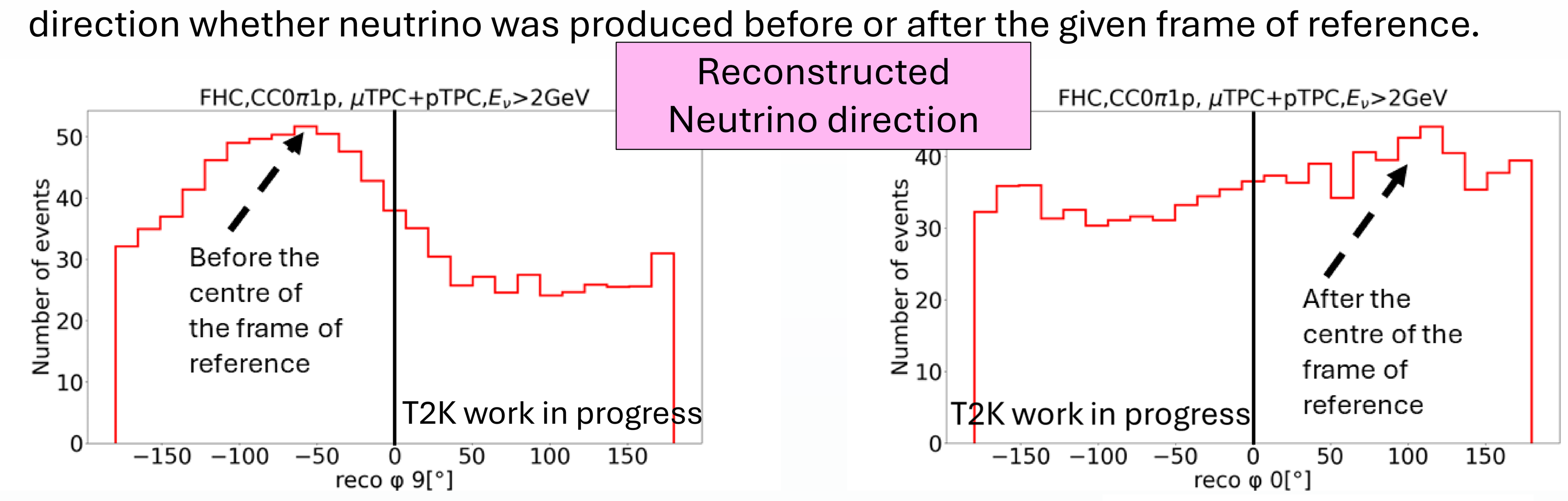


Fig. 7: Example of the reconstructed neutrino direction (φ) for the end of the decay volume (left) and the beginning of the target (right).

- Neutrinos produced **before** the selected reference frame centre -> average φ < **0°**.
- Neutrinos produced **after** the selected reference frame centre -> average φ > **0°**.

Results

Monte Carlo **true** VS **reconstruction** comparison

Neutrino energy reconstruction*:

$E_\nu = E_\mu + E_p + E_{removal} - M_N$, where $E_p = \sqrt{P_p^2 + M_p^2}$, $E_\mu = \sqrt{P_\mu^2 + M_\mu^2}$, $E_{removal} = 28\ MeV$ [4]

*different from the energy reconstruction in T2K oscillation analysis.

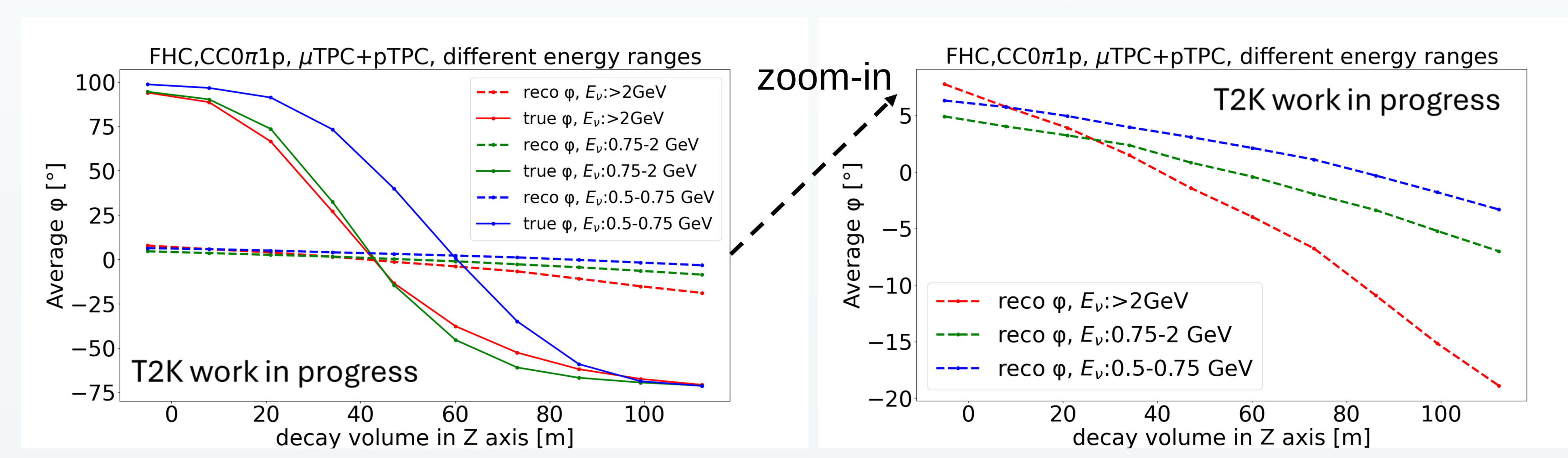


Fig. 8: True and reconstructed average φ values with respect to the decay volume in the Z direction (left) and the reconstructed average φ values (right).

The difference between true and reconstructed quantities arises from nuclear effects, impacting the outgoing muon and proton. Despite this, the Monte Carlo (MC) true and reconstructed quantities exhibit the same trend—both show decreasing slopes. In the true MC, the distributions of the φ are more sharply peaked (Gaussian-like), whereas the reconstructed φ distributions are broader.

Monte Carlo VS **Data** comparison

Differences in simulation and data can help reveal information on potential misalignments in:

- The detector.
- The beam.
- The average decay position of the parent particles in the decay volume.

Data: FHC (250kA) mode: run 2,3,4,8. Number of POT: 9.78x10^{20}, number of events: 2950.

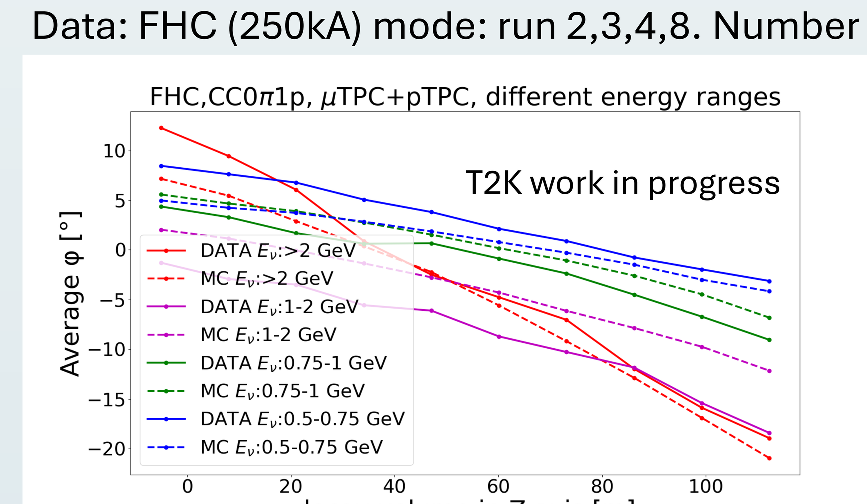


Fig. 9: Reconstructed average φ values with respect to the decay volume in the Z direction for reconstructed MC and data events.

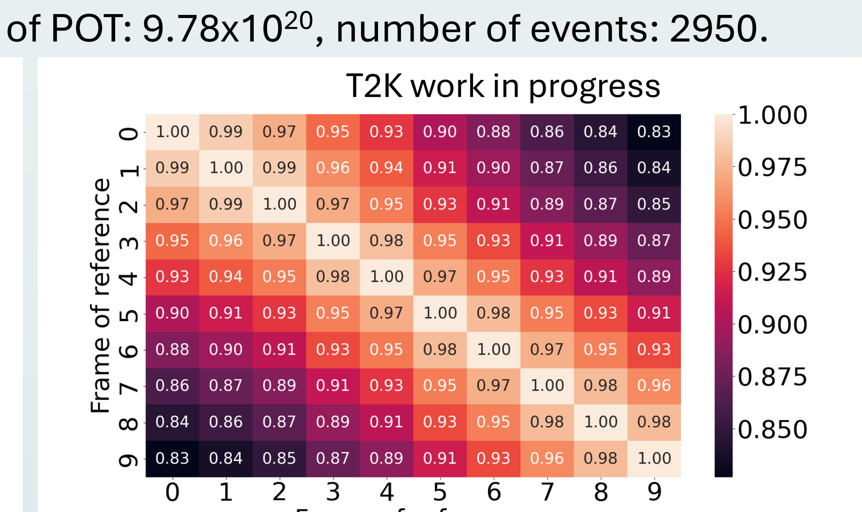


Fig. 10: Correlation matrix for the average φ of each centre of the frame of reference for the energy region 0.5-0.75 GeV.

Statistical error calculations: The averages of φ versus the distances are strongly correlated - they share the same events (Fig. 10). We provided the values for the first centre of the reference system (Fig.11) and the difference of each subsequent point from the first point (Fig.12).

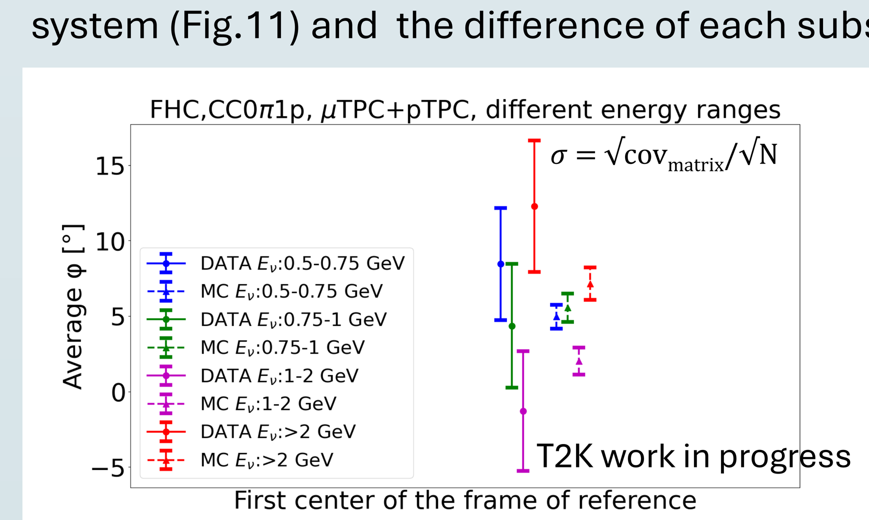


Fig. 11: The average φ values for the first centre of the frame of reference*.

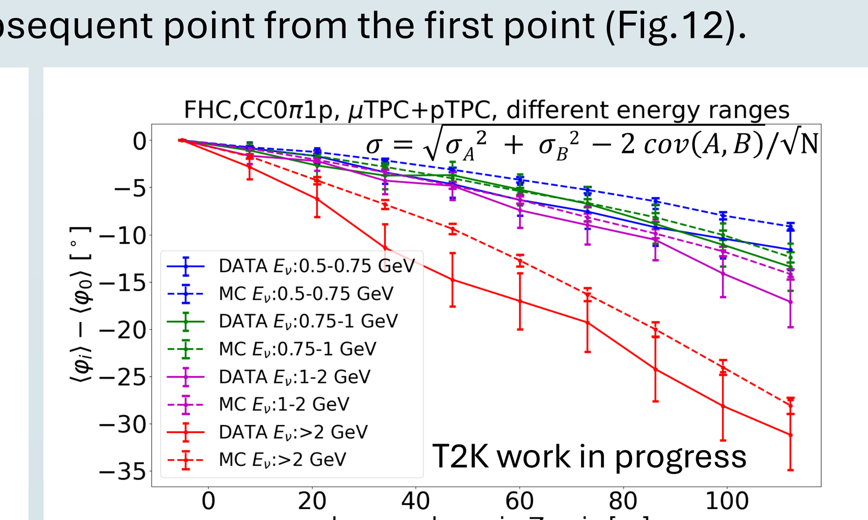


Fig. 12: The difference of each subsequent point (average φ) from the first point.

*the results are shifted along the X-axis to improve visualization of the values on a single plot.

Conclusion

- The proposed **experimental observable**, with higher statistics, may provide information about the dynamics of the beam such as the average decay position of parent neutrinos and insights into detector and beam alignment.
- Sensitivity increases when rotating the reference frame, highlighting different parent decay positions.
- Comparison with MC simulations and data is consistent within 1σ for E_ν < 2 GeV.
- Enhances understanding of neutrino off-axis angles and their energy distribution.
- Potential to add an additional systematic in the energy reconstruction.

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[1] T2K Collab., https: //t2k-experiment.org/t2k/
[2] Beavis, D., A. Carroll, and I. Chiang. "Long baseline neutrino oscillation experiment at the AGS." Physics Design Report Brookhaven National Lab (1995).
[3] Abe, Kou, et al. "T2K neutrino flux prediction." Physical Review D—Particles, Fields, Gravitation, and Cosmology 87.1 (2013): 012001.
[4] Douqa, Dana, et al. "Superscaling variable and neutrino energy reconstruction from theoretical predictions to experimental limitations." Physical Review D 109.7 (2024): 073001.