Effects of the LBNF Neutrino Beam Focusing Uncertainties on DUNE Neutrino Fluxes with a Focus on the Decay Pipe

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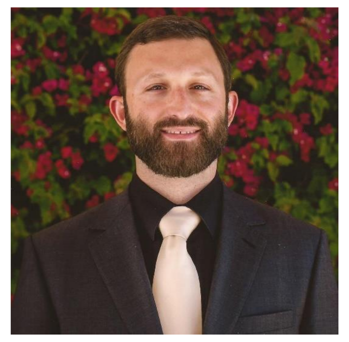
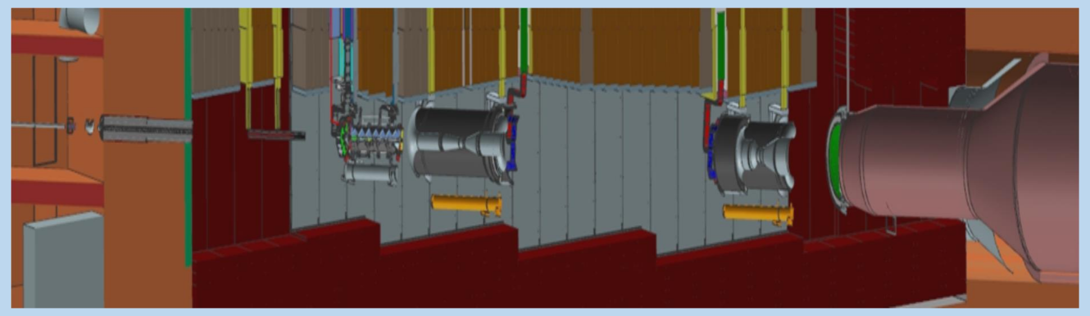
DUNE Deep Underground Neutrino Experiment

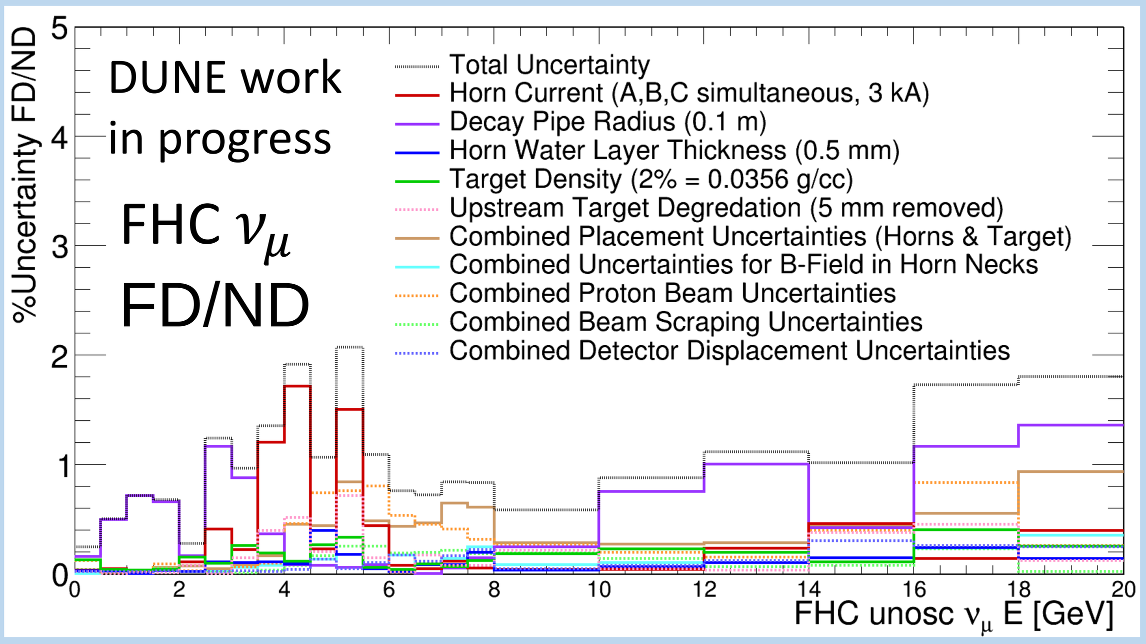


The Deep Underground Neutrino Experiment (DUNE) is a next generation long baseline neutrino experiment which will study the neutrino beam produced by the Long Baseline Neutrino Facility (LBNF) at Fermi National Accelerator Laboratory. Precision measurements of neutrino oscillation parameters with DUNE require estimates of neutrino flux uncertainties. The sources of uncertainties include those from hadron production (dominant) and those due to so-called beam focusing effects. Beam focusing uncertainties arise from the engineering tolerances for the elements in the LBNF beamline used to focus the beam. Some of these elements include the magnetic focusing horns, the geometry of the decay pipe, and the horn currents. The decay pipe can be seen on the right side of the beamline picture below.

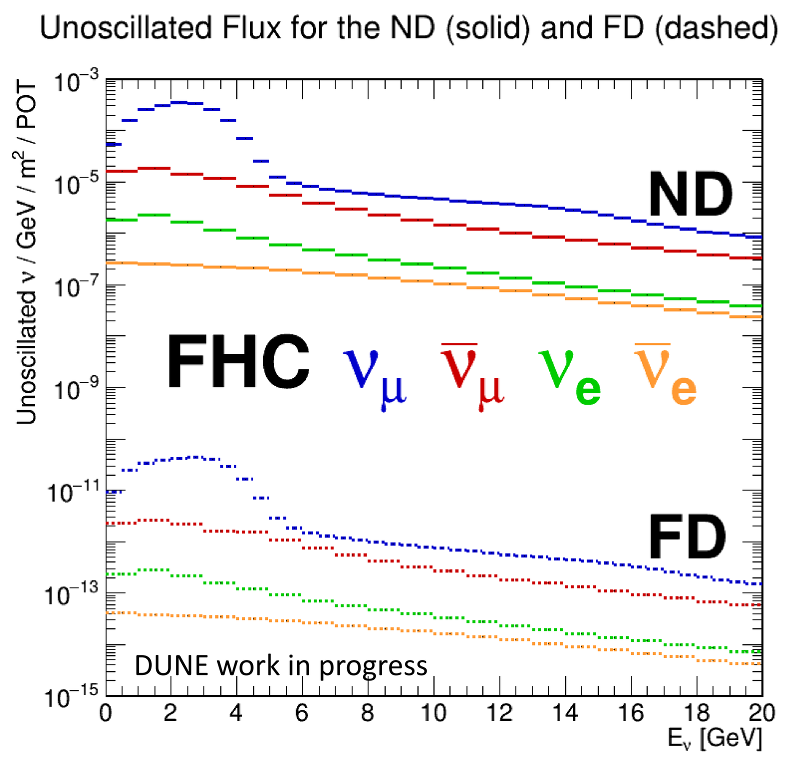


For DUNE's neutrino oscillation physics, the relevant data is the ratio of the flux spectra from the Far Detector (FD) to the Near Detector (ND), and specifically the ν_μ & $\bar{\nu}_\mu$ flux. The region-of-interest (ROI) is below 4.5 GeV where most of the neutrino flux lives.

The dominant uncertainties from a single source for the unoscillated FD/ND ν_μ flux (below) are due to the horn current (red) and the decay pipe (purple). The horn current is dominant from 3.5 – 4.5 GeV, while the decay pipe is dominant below 3.5 GeV.



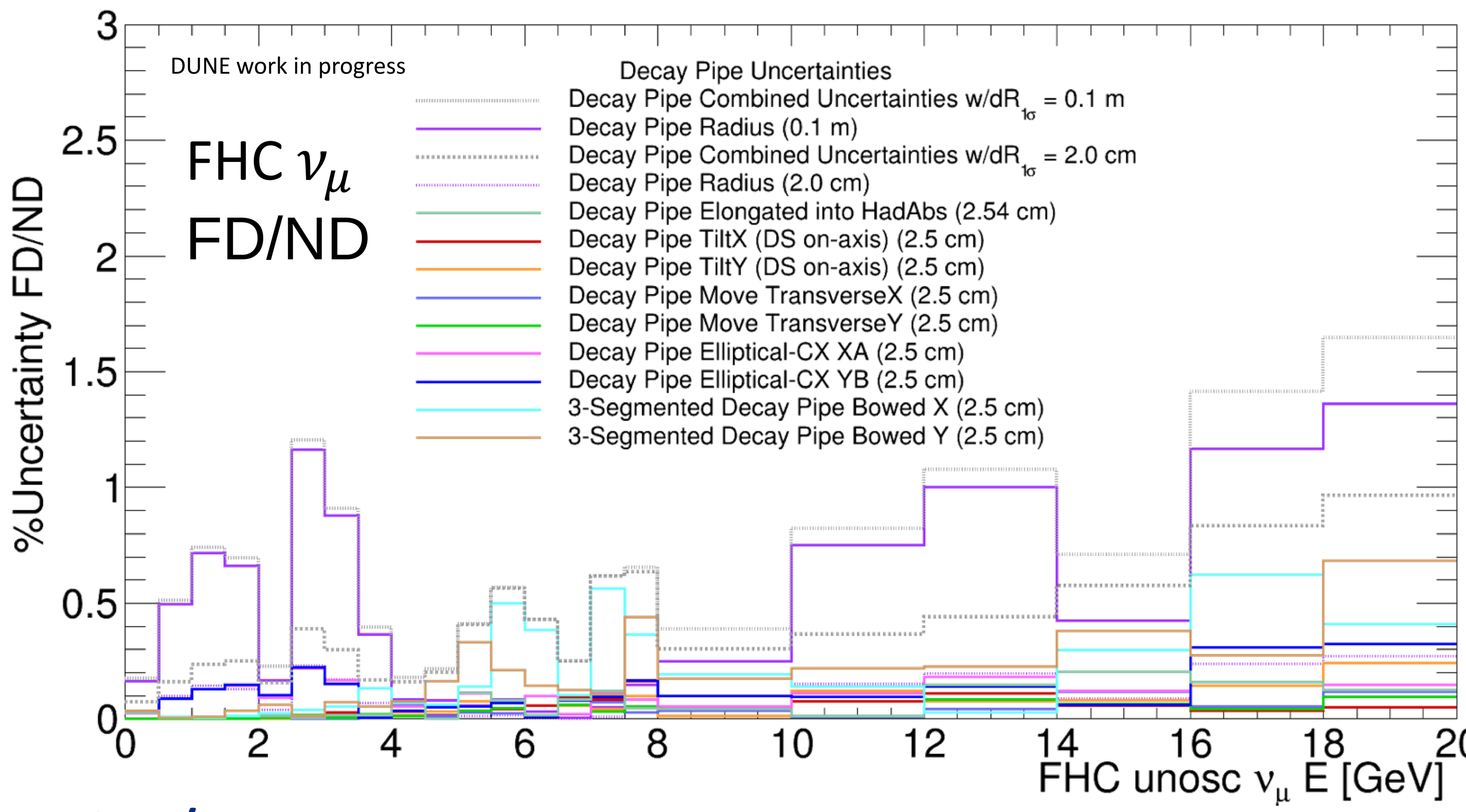
While the hadron production uncertainties are currently dominant, they are expected to substantially reduce over the next few years. This will cause the beam focusing uncertainties to become the dominant sources in the FD/ND ratio, requiring a more thorough evaluation, especially the large contribution from the decay pipe.



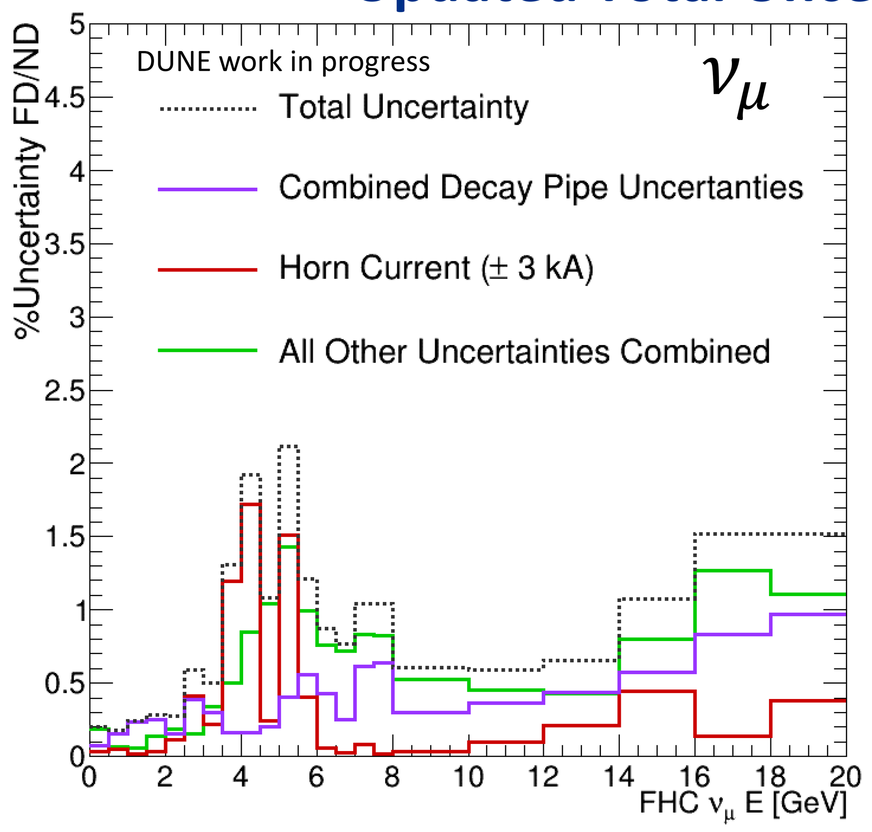
Measurements of ν oscillation parameters with DUNE require understanding the sources of systematic uncertainty on the LBNF ν beam fluxes. The decay pipe is the dominant beam focusing uncertainty in the ROI below 4.5 GeV, but the uncertainty model is (intentionally) simple. It is based only on a 10 cm tolerance of the pipe radius.

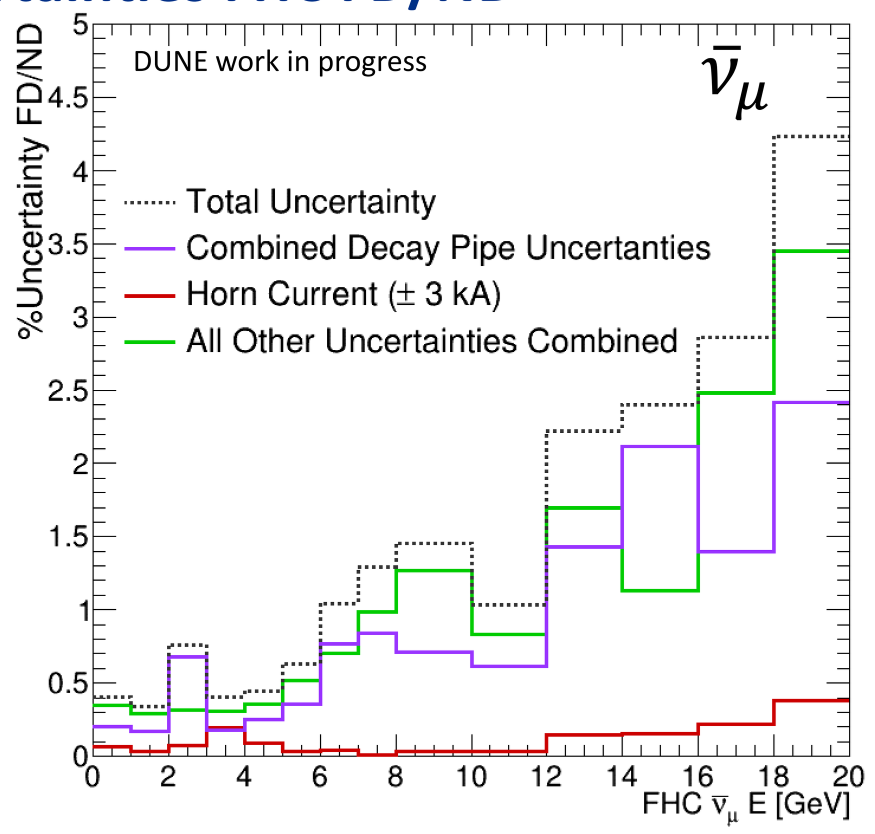
Is this method appropriate for determining this dominant uncertainty?

The actual tolerance for the radius is 2 cm, and additional sources of uncertainty for the pipe exist (right). After accounting for these, the 10 cm radial tolerance over-estimates the uncertainty in the ROI and fails to capture other features.

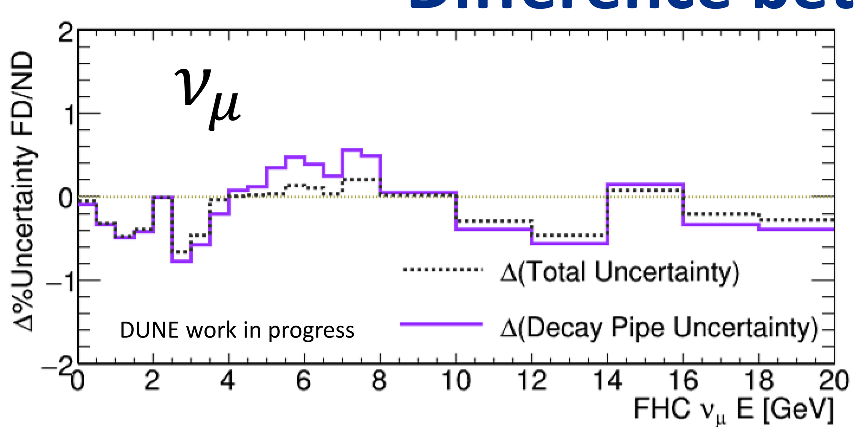


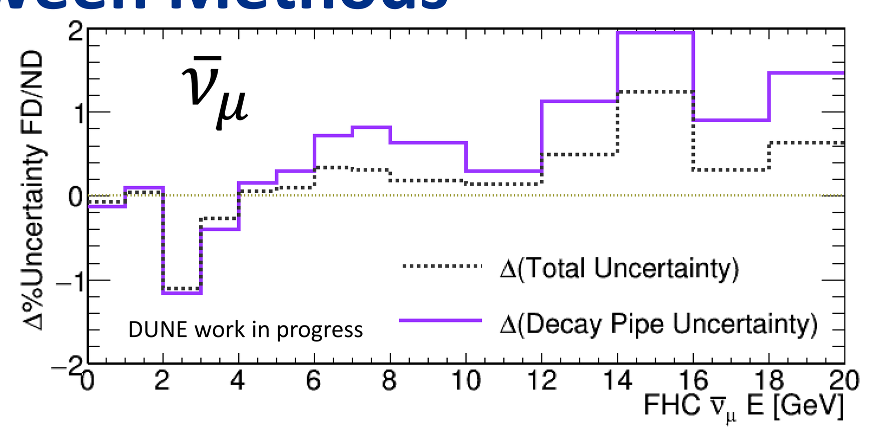
Updated Total Uncertainties FHC FD/ND





Difference between Methods





The updated method captures alternative effects the simple model could not while reducing the overall uncertainty in the ROI from the decay pipe for ν_μ & $\bar{\nu}_\mu$.

Left: The resulting total beam focusing uncertainties for ν-beam mode FD/ND flux ratios.

Bottom: The difference for the decay pipe uncertainty & for the total beam-focusing systematic uncertainty (gray) between using the simple & updated method for the decay pipe uncertainty.

With the traditional method for determining the decay pipe's contribution, this source's uncertainty is similar in scale to the current hadron production uncertainty. However, is this method appropriate?

The decay pipe's contribution to the uncertainty has traditionally been estimated using a 10 cm tolerance based on the expected possible variation of the 2 m radius from one end of the decay pipe to the other. In simulations, the radius is modified by the tolerance but is constant for entire length of the pipe. Additionally, 2 cm is the maximum variation allowed for the radius in the pipe's construction.

This model for the uncertainty is simplistic and does not capture the effects that other sources of uncertainty arising from the construction and settling of the decay pipe. Additional sources and their tolerances include:

- **Deformations resulting in elliptical cross-sections: 2 cm**
- **Longitudinal bowing of the pipe via segmentation into 3 pieces: 2 cm**
- **Tilting due to ground settling: 3 mm**
- **Axial misalignment tolerances: 1 mm**
- **Thermally induced elongation of the pipe: 2.54 cm for 1.2 MW beam**

For all but the last source listed, the tolerances were over-estimated at 2.5 cm in this study. The results presented are for the LBNF neutrino-beam mode (FHC).

Taking these additional sources into account and using the appropriate radial variation, the radial tolerance dominates the decay pipe uncertainties, with the elliptical deformations in second. The combined systematic uncertainties from the decay pipe still dominate the FD/ND flux ratios below 3.5 GeV. However, the combined uncertainties contribute significantly less for the ν_μ & $\bar{\nu}_\mu$ and free up the error budget in this region.

The simulations used to extract the beam focusing uncertainties will be used to create a covariance matrix to understand how all the uncertainties are correlated.