Neutrino Beam Simulations for the Hyper-Kamiokande experiment and target alternatives

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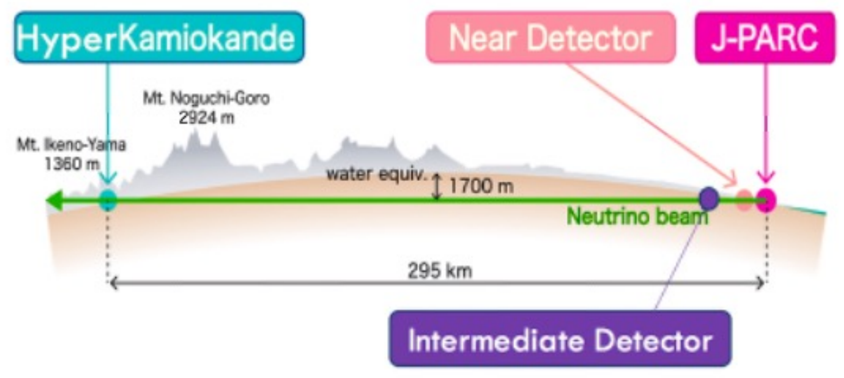
The Hyper-Kamiokande Experiment (Hyper-K)

Hyper-K will be the world's largest nucleon decay and neutrino experiment detector. It is set to start operation in 2027. It will continue the successful history of the Kamiokande, Super-Kamiokande, and T2K experiments., studying oscillation parameters such as mixing angles, mass differences and CP-violating phase.

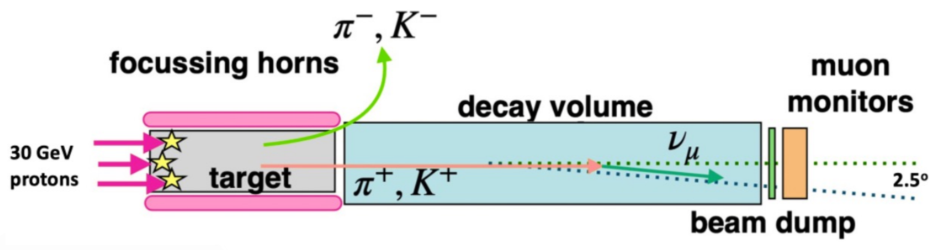
Long baseline program:

J-PARC → Near Detector → Intermediate Detector → Far Detector

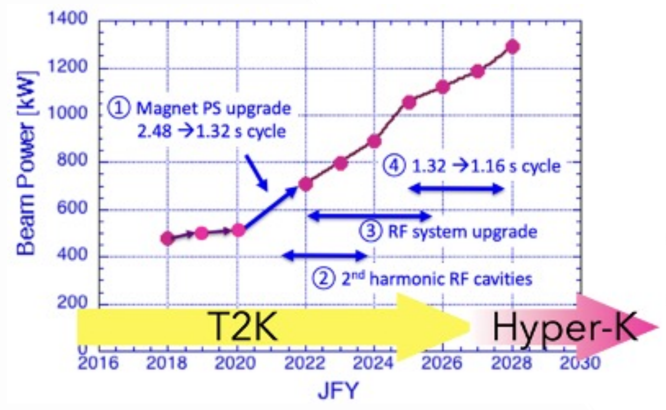


A 30 GeV proton beam from J-PARC impinges on a carbon target producing secondary hadrons.

The charged particles are then focused/defocused by three **magnetic horns**.

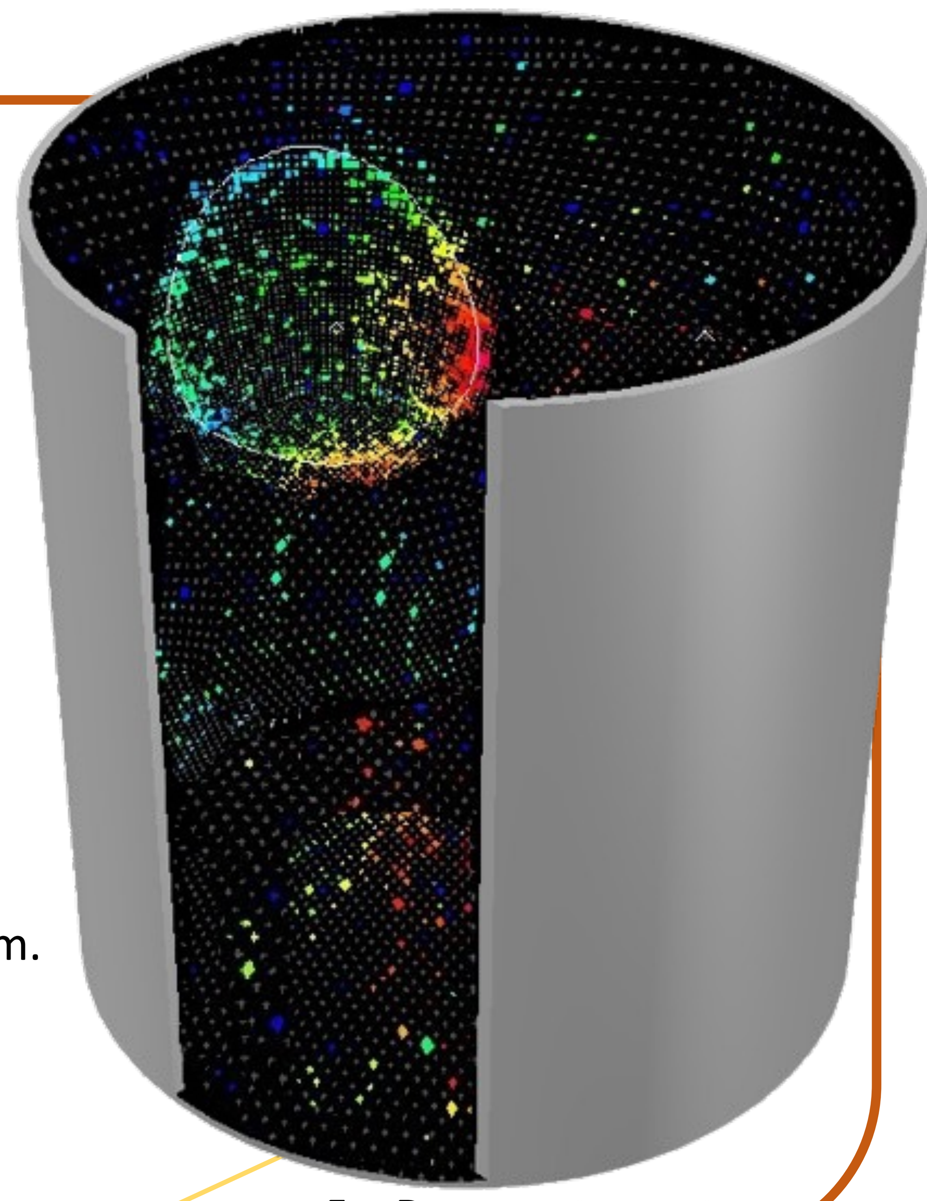


Hadrons eventually decay in a decay volume, producing a **neutrino beam**.

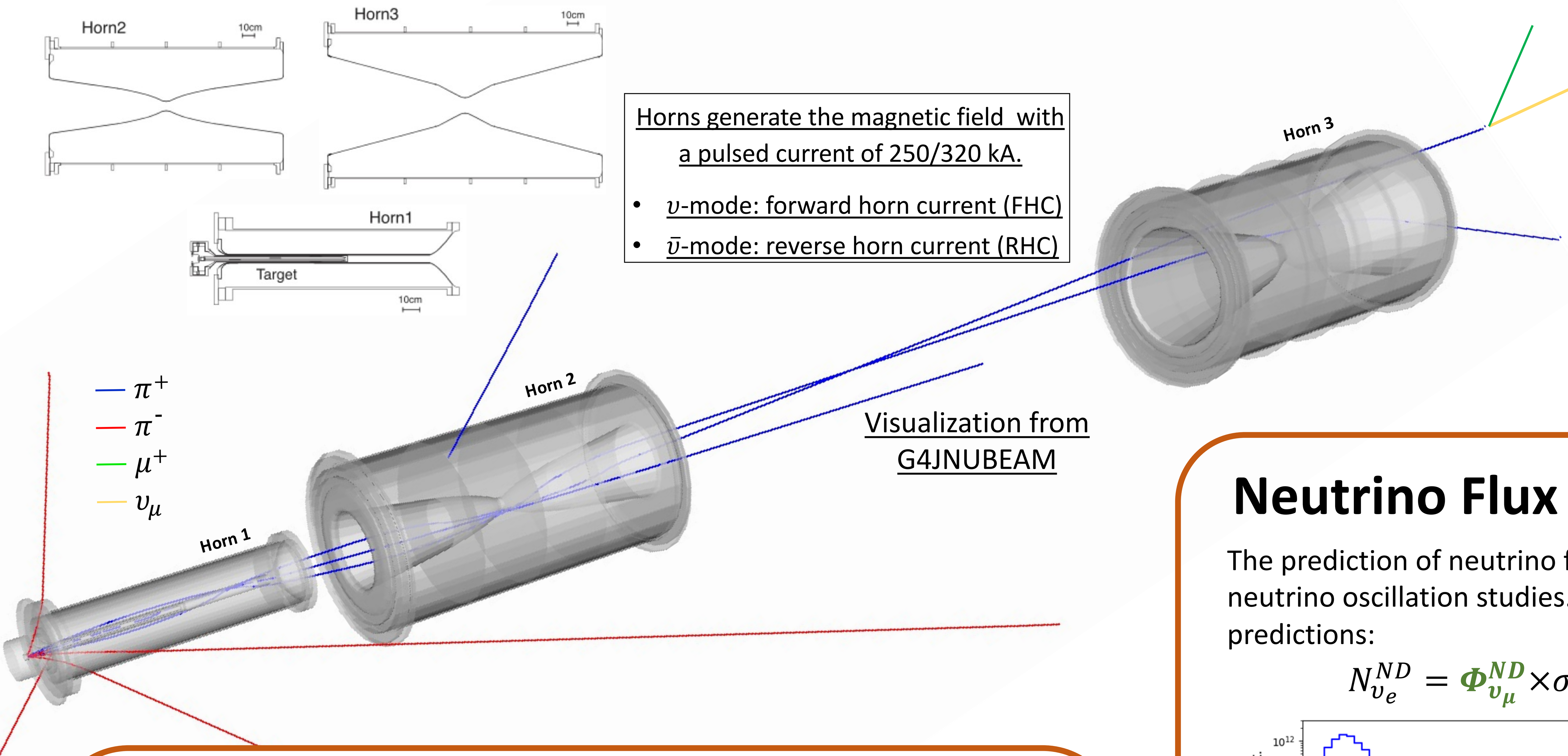


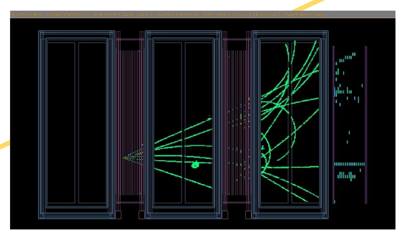
Hyper-K will have an upgraded neutrino beam.

Goal: 1.3 MW Beam Operation.



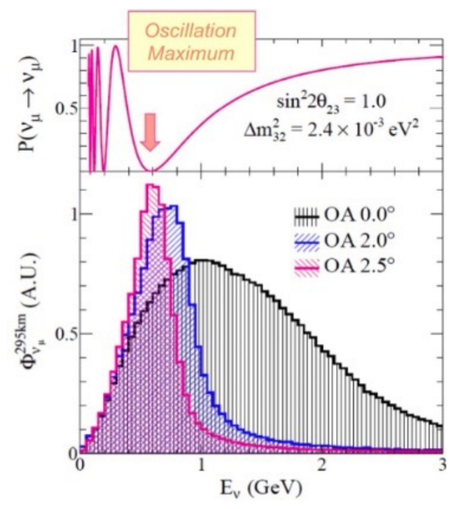
Far Detector (295 km)





Near Detector (280 m)

Hyper-K will continue using the off-axis beam configuration used in T2K.

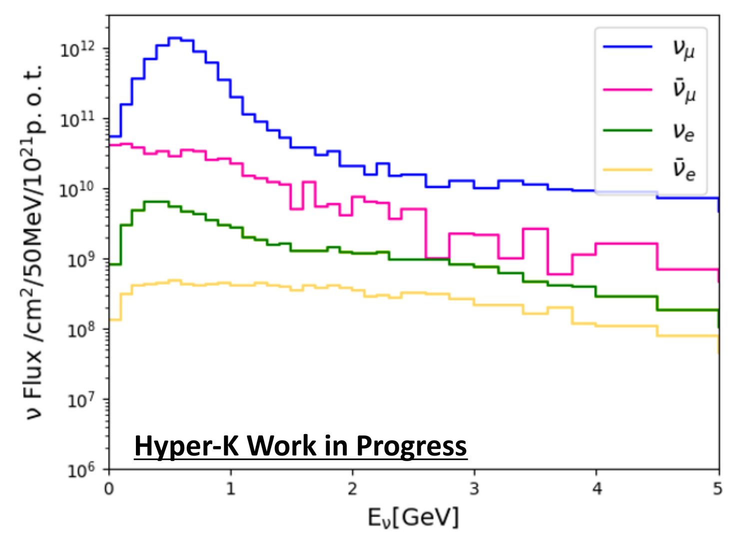


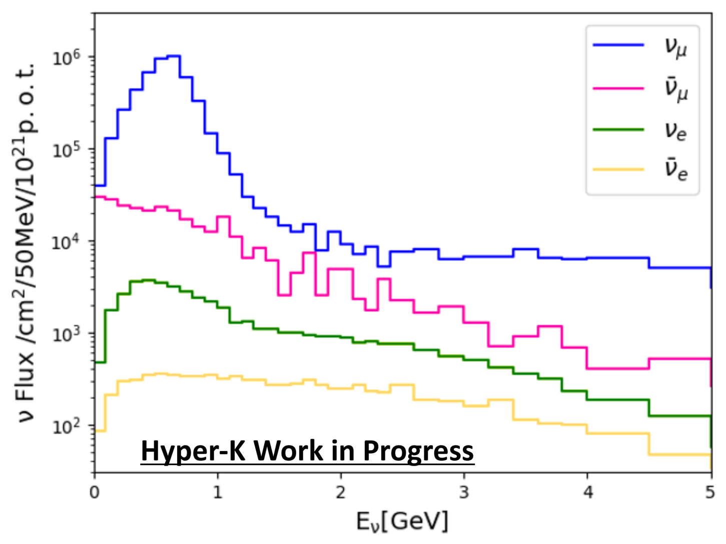
Neutrino fluxes for off-axis angles 0.0°, 2.0° and 2.5° [1]

Neutrino Flux Predictions

The prediction of neutrino fluxes at both near and far detectors is essential for neutrino oscillation studies. G4JNUBEAM can be utilized to obtain these predictions:

$$N^{ND}_{\nu_e} = \Phi^{ND}_{\nu_\mu} \times \sigma^{ND}_{\nu_e} \qquad N^{FD}_{\nu_e} = P_{\nu_\mu\rightarrow\nu_e} \times \Phi^{FD}_{\nu_\mu} \times \sigma^{FD}_{\nu_e}$$





Neutrino fluxes at near detector (left) and far detector (right) for forward horn current configuration (320 kA) generated with G4JNUBEAM.

Predictions from G4JNUBEAM will be tuned using external data (e.g., NA61/SHINE replica target [5], same as JNUBEAM.)

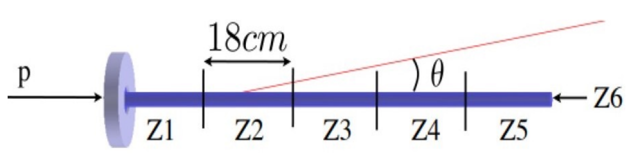
Beam Simulations: G4JNUBEAM

A GEANT4 [2] neutrino beam simulation framework, G4JNUBEAM, is currently being developed for both the T2K and Hyper-K experiments.

- Built on the existing T2K simulation package, JNUBEAM [1] (based on FLUKA [3] and GEANT3 [4]).
- Geometry converted from JNUBEAM to GDML format.
- Optimised magnetic field implementation.
- Framework is almost complete, already produces preliminary neutrino flux spectra.

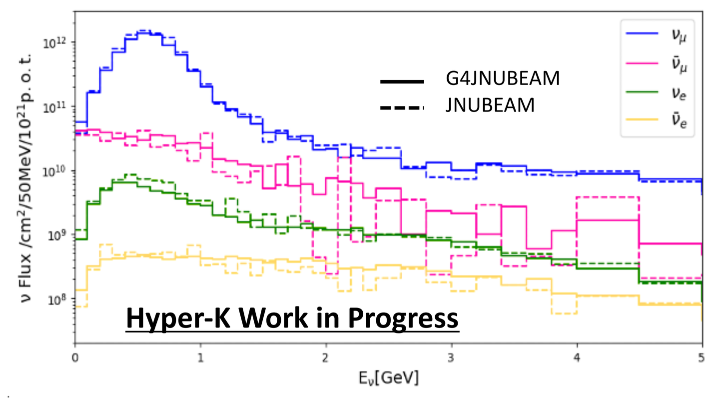
Validation of G4JNUBEAM

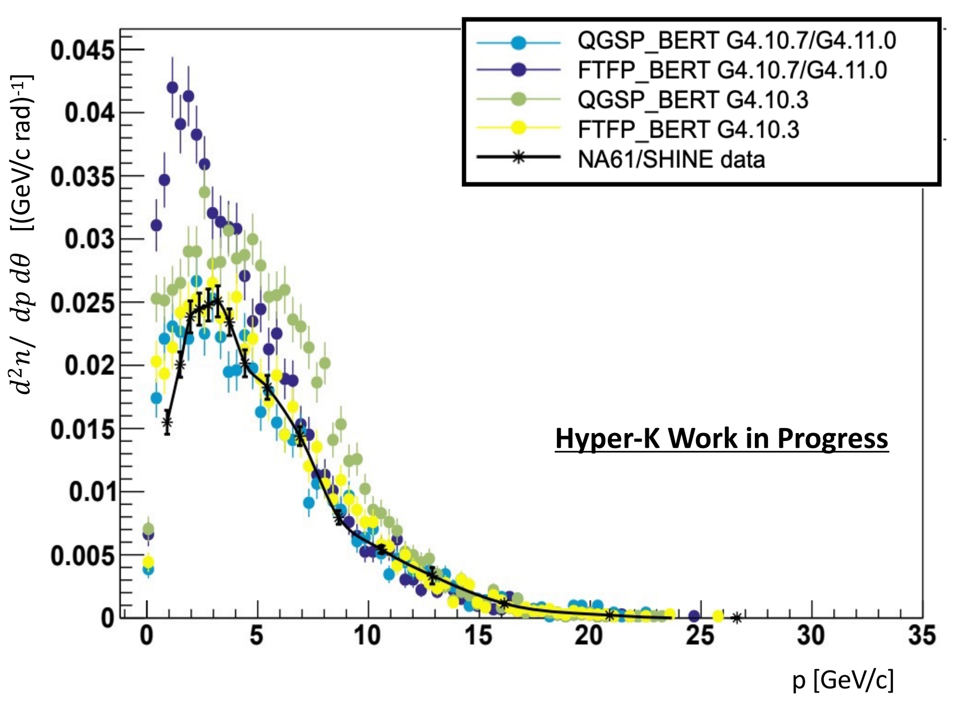
Data from NA61/SHINE 2010 run (T2K replica target) [5] is used for validation of G4JNUBEAM.



NA61/SHINE data: double yield differential data for different target segments.

Also used to benchmark physics list and GEANT4 version.





Pion yields from G4JNUBEAM simulations (markers) and NA61/SHINE data (solid line) for last 18 cm (Z5) downstream of the target. (20-40 mRad).

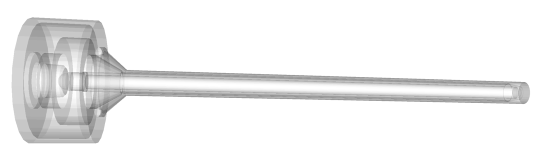
To validate the neutrino fluxes, G4JNUBEAM results are compared with those from JNUBEAM.

Study of Target Alternatives

The rate of particles that won't enter the magnetic field, and consequently increase the wrong sign contamination in the neutrino flux, is decreased as the length/density of the target increases.

Alternative target options for Hyper-K are being studied:

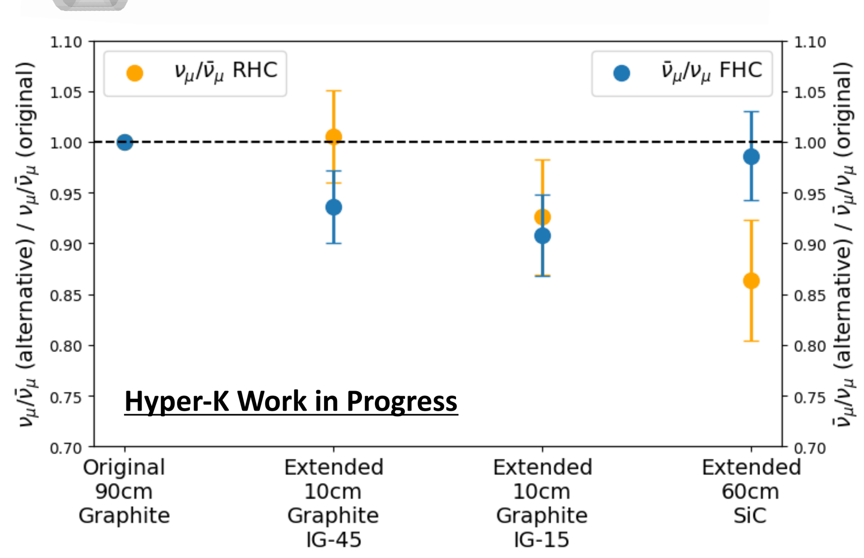
Original Target: 90-cm graphite (IG-43 1.82 g/cm³) rod



90-cm graphite (IG-43 1.82 g/cm³) rod + 60-cm Silicon Carbide (3.21 g/cm³) rod

100-cm graphite rod, with IG-45 (1.88 g/cm³) and IG-15 (1.90 g/cm³)

Simulations show a decrease in the wrong-sign contamination as the target length and density increase.



Double ratio of wrong-sign contamination (target alternative/original) in neutrino flux for various target lengths and densities.

References: **[1]** K. Abe et al., "T2K neutrino flux prediction," Phys. Rev. D 87, 012001 (2013), **[2]** S. Agostinelli et al., "Geant4 - A Simulation Toolkit," Nucl. Instrum. Meth. A 506 (2003) 250-303, **[3]** G. Battistoni et al., "Overview of the FLUKA code," Annals of Nuclear Energy 82, 10-18 (2015), **[4]** R. Brun et al., "GEANT3," CERN-DD-EE-84-1, **[5]** N. Abgrall et al., "Measurements of π±, K± and proton yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS," Eur.Phys.J. C79 (2019) no.2, 100.