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# Neutrino flux simulation for T2K using GEANT4

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The precise knowledge of neutrino flux and related uncertainties at the near and far detectors of the T2K experiment is crucial for extracting various neutrino oscillation parameters and neutrino cross-section measurements. The current Monte Carlo beam simulation framework, JNUBEAM, relies on the GEANT3 toolkits, which are no longer maintained. Additionally, it utilizes the FLUKA software to simulate hadronic production from interactions of the proton beam with the target. We aim to create a replacement framework solely based on well-established GEANT4 toolkits. Our new framework, namely G4JNUBEAM, uses GEANT4 available physics processes to consider primary proton interactions in the T2K target through to the decays of muons and hadrons, and subsequent production of neutrinos. We present simulation results for validation against NA61/SHINE data, neutrino flux predictions using G4JNUBEAM, and comparisons with the results obtained from the FLUKA+JNUBEAM simulations.

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## 1. Introduction

The Tokai-to-Kamioka (T2K) is a leading accelerator-based neutrino experiment in Japan that produces an intense neutrino beam with a narrow peak in energy to study neutrino interaction and determine the oscillation parameters with significant accuracy. The T2K experiment is in particular sensitive to the Charge Parity (CP) violating phase ($\delta_{CP}$) and aims to find $3\sigma$ confidence if there is a maximal CP violation in the leptonic sector. The neutrino beam is generated on the east coast of Japan at Tokai and directed towards the gigantic neutrino detector, the Super-Kamiokande (SK), a 50 kton water Cherenkov detector, located at Kamioka, 295 km away from the beam's origin. The process of neutrino beam generation starts with the primary hadron (i.e., $\pi^{\pm}, K^{\pm}$, p, $\Lambda$, etc.) production by illuminating a 91.4 cm long, 2.6 cm diameter graphite target with a 31 GeV/c proton beam, (recently achieved power of 800 kW) generated by the J-PARC accelerator facility [1]. These hadrons are then focused by three powerful magnetic horns (with positive or negative polarity) and subsequently decay in a 96 m long decay volume to produce a narrowband intense $\nu_{\mu}$(or $\overline{\nu_{\mu}}$) beam (see Fig. 1).

The oscillation studies at T2K are conducted at 2.5° off-axis from the proton beamline, where

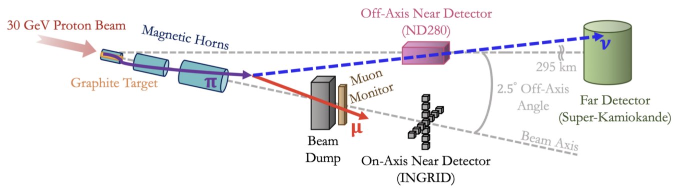


**Figure 1:** Schematic of Tokai to Kamioka (T2K) experiment producing $\nu_{\mu}$-beam.

two major detectors are located. The Near Detector (ND280), situated 280 m from the beam origin, constrains the produced neutrino flux and measures the neutrino cross-sections. The Far Detector at Super-Kamiokande measures the neutrino flavor and kinematics and extracts the oscillation parameters using both the near and far detector models and the data-driven constraints.

The neutrino flux predictions and associated uncertainties at various detector planes play a significant role in constraining the oscillation parameter space and reducing the total uncertainties.

## 2. T2K Neutrino Flux Simulation : JNUBEAM

The present Monte Carlo flux simulation model for T2K, called JNUBEAM [1], is a complex framework based on multiple detector simulation packages, namely FLUKA [2] and GEANT3. The FLUKA is used for interactions inside the target, whereas, GEANT3 (with GCALOR physics model) is used for the interactions and propagation of particles in other beamline volumes, including horns, decay volume, dump materials, etc. Since GEANT3 has not been maintained for over twenty years, and beam simulations will extend to the next-generation Hyper-Kamiokande experiment, adopting GEANT4-based simulation offers a more modern approach for neutrino flux simulation.

## 3. GEANT4-based Framework : G4JNUBEAM

A new framework, based on only GEANT4 toolkits [3], called G4JNUBEAM, is currently being developed to replace the existing Monte Carlo beam simulation JNUBEAM. The framework has flexible geometry compatibility with the GDML (Geometry Description Markup Language) format and can utilize various built-in GEANT4 physics models for detector simulations. The framework considers all physics processes from primary proton-hadron interactions inside the target to secondary hadronic interactions both in and outside the target, as well as the subsequent weak decays of hadrons and muons that produce neutrinos.

### 3.1 Validation with NA61/SHINE data

As a benchmark, we first validate hadron production from proton beam interactions with the replica target geometry by comparing the results from our G4JNUBEAM framework with the measured NA61/SHINE data [4] from the 2010 run. Figure 2(a) presents a comparison of the double differential $\pi^-$ yields (i.e., $d^2n^{\pi^-}/dpd\theta$) from 18–36 cm downstream of the target at angles of 20 to 40 mrad, as measured by the NA61/SHINE experiment, with the results from the G4JNUBEAM framework using various GEANT4 versions (v10.3, v10.7, v11.0, and v11.1) and physics models (QGSP_BERT and FTFP_BERT). The simulation results using the QGSP_BERT physics list and GEANT4 versions v10.7, v11.0, and v11.1 are found to match well with the data. The results using the FTFP_BERT physics list show the closest agreement for the GEANT4 version v10.3.

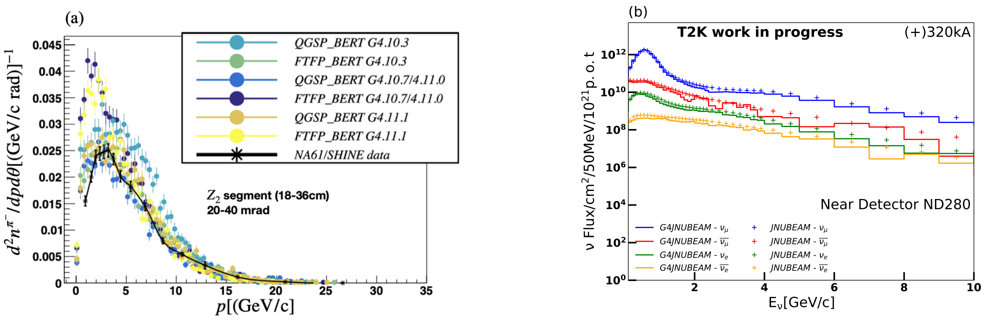


**Figure 2:** (a) Double differential $\pi^-$ yields from replica target at NA61/SHINE [4] and benchmarking using different physics models of GEANT4. (b) Comparison of neutrino fluxes at ND280 using G4JNUBEAM and JNUBEAM.

### 3.2 Preliminary Results

In Figure 2(b), we show a comparison of the near detector (ND280) neutrino fluxes of different flavors in the neutrino $\nu$-beam mode, with a 320 kA horn current, as obtained from both G4JNUBEAM and JNUBEAM simulations. The neutrino fluxes from G4JNUBEAM, using GEANT4 v11.1 with the FTFP_BERT physics list, show overall good agreement with those obtained from JNUBEAM. However, we observe a substantial difference in the $\overline{\nu_e}$ fluxes around the peak energy region ($\sim$ 600 MeV), which is currently under investigation. Additionally, the high-energy fluxes (above 3 GeV) from G4JNUBEAM have limited statistics. The G4JNUBEAM fluxes are yet to be tuned with NA61/SHINE data [4] and the software is currently being optimized for this purpose.

## References

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