PROCEEDINGS OF SCIENCE

Development of T2K Beam Simulation with GEANT4

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The long baseline neutrino experiment T2K has successfully used Monte Carlo simulations for the neutrino flux predictions in both near and far detectors, which are essential inputs for different neutrino oscillation and cross section analyses. However, the current simulation software is based on FLUKA and the no-longer maintained simulation package GEANT3, which is becoming difficult to support. A replacement beam simulation using the GEANT4 software package is in development, aiming to describe the physical processes from the primary proton interactions in the T2K target to the decay of hadrons and muons, producing neutrinos for the flux predictions at both near and far detectors. The T2K flux simulation is generally tuned using measurements from the NA61/SHINE spectrometer of $\pi^{\pm}$, $K^{\pm}$ and proton differential yields emitted from a T2K replica target, and those measurements can also be used to validate the new simulation software. We present the recent simulation results for the validation with NA61/SHINE data, the neutrino flux predictions, and comparisons to the current FLUKA/GEANT3 simulations.

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1. The T2K Experiment and Neutrino Beam

The T2K (Tokai-to-Kamioka) is a long baseline neutrino experiment located in Japan. A neutrino beam is produced at the accelerator facility at the Japan Proton Accelerator Research Center (J-PARC) and travels from the east to west coasts of Japan, as illustrated in Figure 1. T2K studies the oscillation of neutrinos, observing the disappearance of ν_μ and appearance of ν_e, aiming to determine the value of oscillation parameters and to search for CP violation in the leptonic sector.

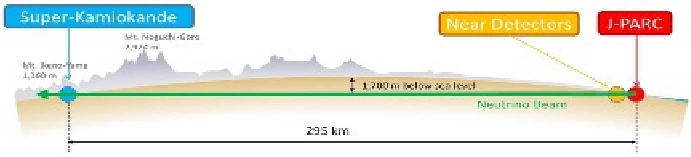


Figure 1: The T2K experiment.

The neutrino beam is measured 280 m after production at the near detector complex, which contains the detectors ND280, INGRID and WAGASCI/BabyMIND. The beam is then again measured 295 km away at the far detector Super-Kamiokande. ND280 and Super-Kamiokande are 2.5° off-axis with respect to the beamline and in this configuration a narrow neutrino spectrum with a peak energy of approximately 0.6 GeV is generated.

The neutrino beam is produced by impinging a 30 GeV proton beam produced at the J-PARC main ring on a carbon target, producing secondary hadrons, which are focused by three magnetic horns and eventually decay into neutrinos in a 96 m-long decay volume. Figure 2 shows a schematic view of the neutrino beam production.

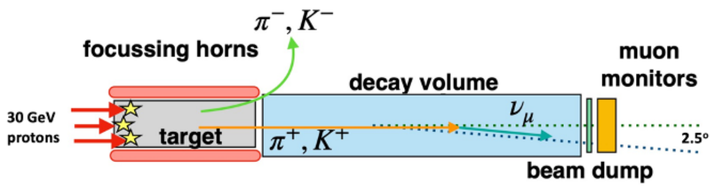


Figure 2: Schematic view of the proton beam interacting in the T2K target.

The target is a 90 cm long graphite rod (placed inside the first horn) surrounded by a titanium case and its temperature is controlled by allowing helium to flow around it. The magnetic horns, shown in Figure 3, focus the charged hadrons that result from interactions of the protons in the target. The horns generate the magnetic field with a pulsed current of 250/320 kA.

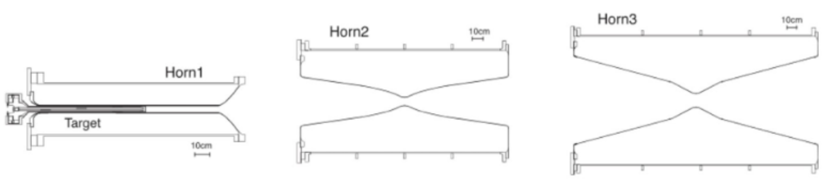


Figure 3: Cross section of the three magnetic horns showing the graphite target inside the first horn. Adapted from [1].

2. T2K Beam Simulations: JNUBEAM

The neutrino beam simulations in T2K, JNUBEAM [1], is based on the no longer maintained simulation package GEANT3 and relies on FLUKA [2] for hadronic interactions inside the target.

One of the main systematic uncertainty sources of the neutrino flux predictions comes from the secondary hadrons produced from the interactions of the proton beam with the target. The neutrino fluxes generated with JNUBEAM are tuned with data taken by the NA61/SHINE experiment [3] of the produced hadrons around a T2K replica target. Figure 4 shows neutrino fluxes from JNUBEAM tuned with NA61/SHINE data.

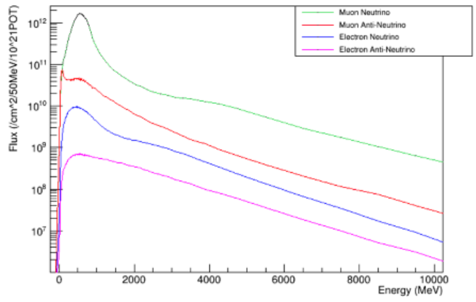


Figure 4: JNUBEAM neutrino fluxes at ND280 for a horn current of 250 kA. From webpage: `https://t2k-experiment.org/result_category/flux` (neutrino beam flux prediction 2020).

Since GEANT3 has not being maintained for over 20 years and the beam simulations will also be carried into the future generation experiment Hyper-Kamiokande, using GEANT4 would be a modern approach to generate the beam simulations, replacing both GEANT3 and FLUKA.

3. GEANT4 Framework - G4JNUBEAM

A new framework, G4JNUBEAM, is under development to replace the beam simulations with a Monte Carlo simulation based on GEANT4, aiming to describe the physical processes from proton interactions in the target to the decay of hadrons and muons producing neutrinos.

The framework uses a converted geometry from JNUBEAM, and it is now almost complete, already available to T2K collaborators. Figure 5 shows a visualization from G4JNUBEAM, showing the horns acting on pions produced in the target. The outputs from the simulation are currently being tested in the T2K flux tuning code, for the NA61/SHINE reweighting.

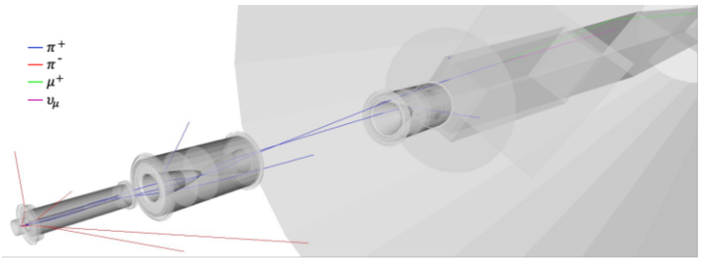


Figure 5: Visualization from G4JNUBEAM.

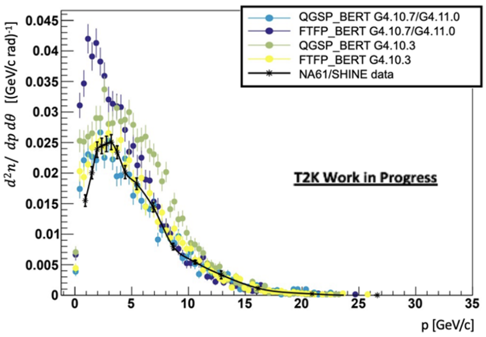
3.1 Validation with NA61/SHINE data

The NA61/SHINE data from the 2010 run [3], which is used for the neutrino beam tuning, was used for the validation of G4JNUBEAM by comparing the hadrons generated from the proton beam interactions in the target from the simulation with the data.

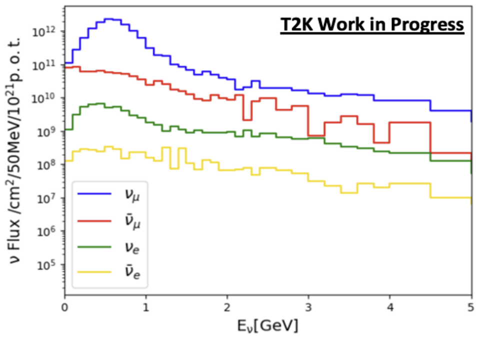
Figure 6a shows a comparison of different GEANT4 versions (v10.3, v10.7 and v11.0) and physics models (QGSP_BERT and FTFP_BERT) to the NA61/SHINE data in the last 18 cm downstream of the target for the pions leaving with an angle of 20 to 40 mrad. Data agrees with the simulation for newer versions of GEANT4 (v10.7 and v11.0) to the physics list QGST_BERT.

3.2 Preliminary Results

The G4JNUBEAM framework is still under development, but some preliminary neutrino flux plots can already be obtained, as shown in Figure 6b. These simulations used GEANT4 version 4.11.0.3 with the QGSP_BERT model.



(a)



(b)

Figure 6: (a) Pion yields from G4JNUBEAM simulations (markers) and NA61/SHINE data (solid line) for the last 18 cm downstream of the target in the 20-40 mrad angular range and (b) G4JNUBEAM neutrino fluxes at ND280 (for a horn current of 320 kA).

G4JNUBEAM fluxes are still not tuned with NA61/SHINE data. The software is currently being optimized to be compatible with the T2K flux tuning.

References

[1] K. Abe et al., *T2K neutrino flux prediction*, *Phys. Rev. D* **87** 012001 (2013).

[2] G. Battistoni et al., *Overview of the FLUKA code*, *Annuals of Nuclear Energy* **82** 10-18 (2015).

[3] N. Abgrall et al., *Measurements of $\pi^{\pm}$, $K^{\pm}$ 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.