Neutrino flux simulation for T2K using GEANT4

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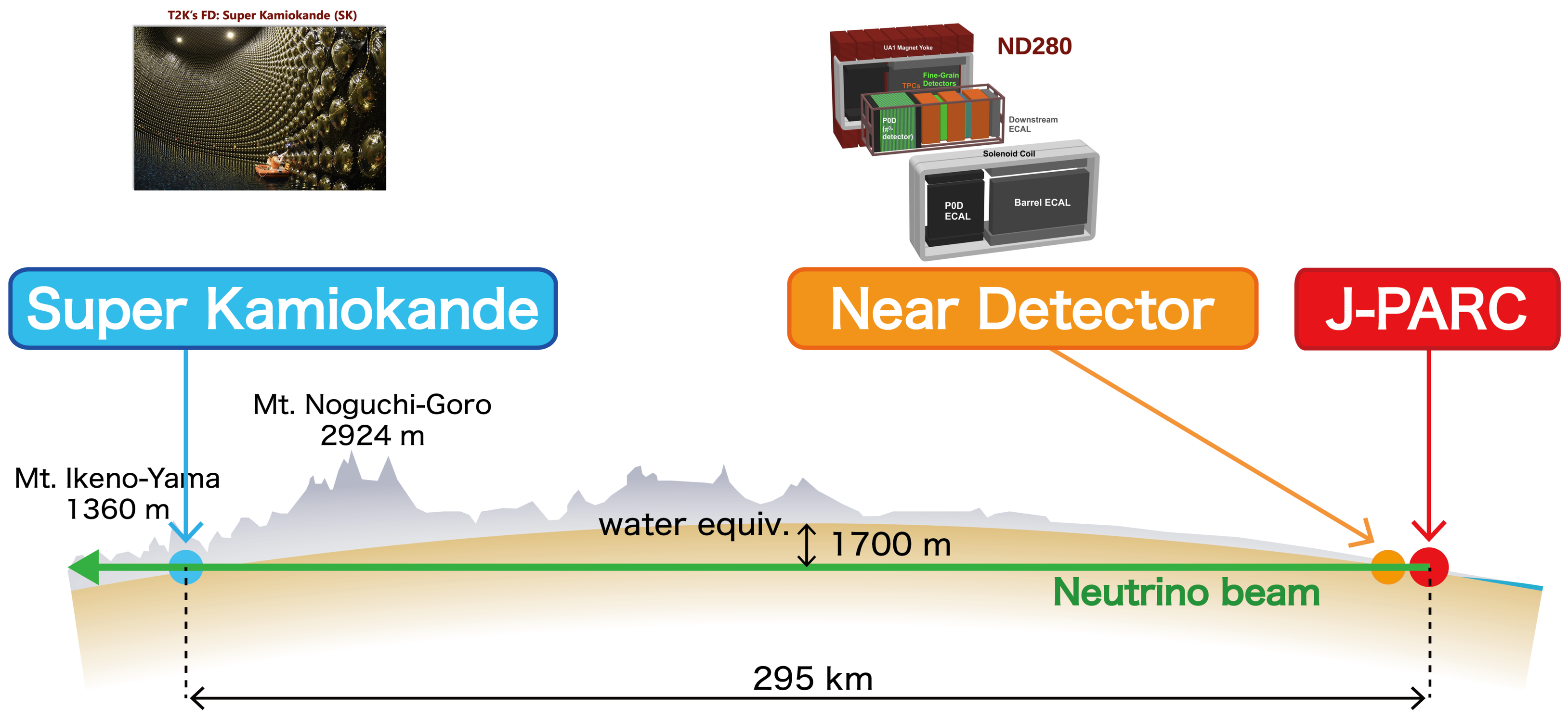
Tokai-to-Kamioka Experiment

T2K (Tokai-to-Kamioka) is an accelerator-based long-baseline neutrino experiment in Japan.
Aim: To measure the three-flavor neutrino oscillation parameters by studying neutrino oscillations at a distance of 295 km.

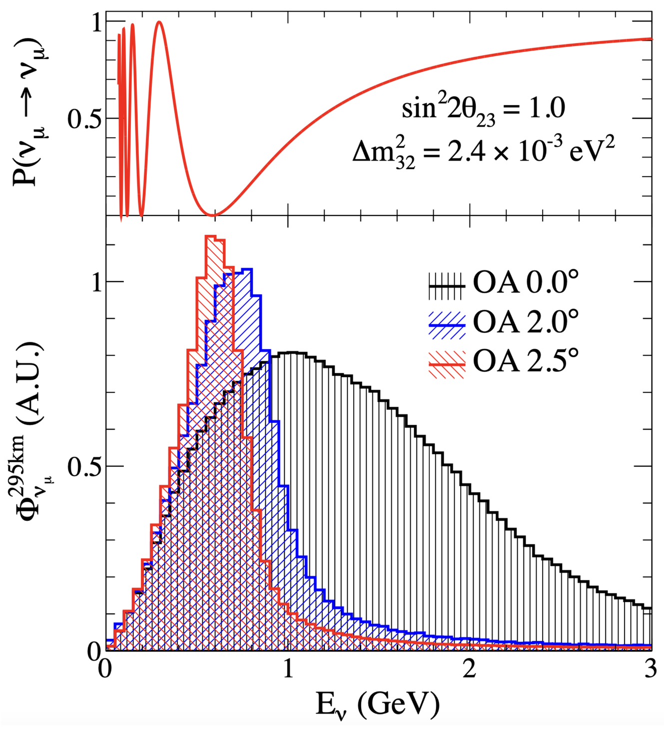


- Both survival $P(\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu))$ and appearance $P(\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e))$ probabilities of $\nu_\mu(\bar{\nu}_\mu)$ beam are studied.
- The T2K can significantly constrain the δ_{CP}-space if there is a maximum Charge Parity (CP) violation in the leptonic sector.

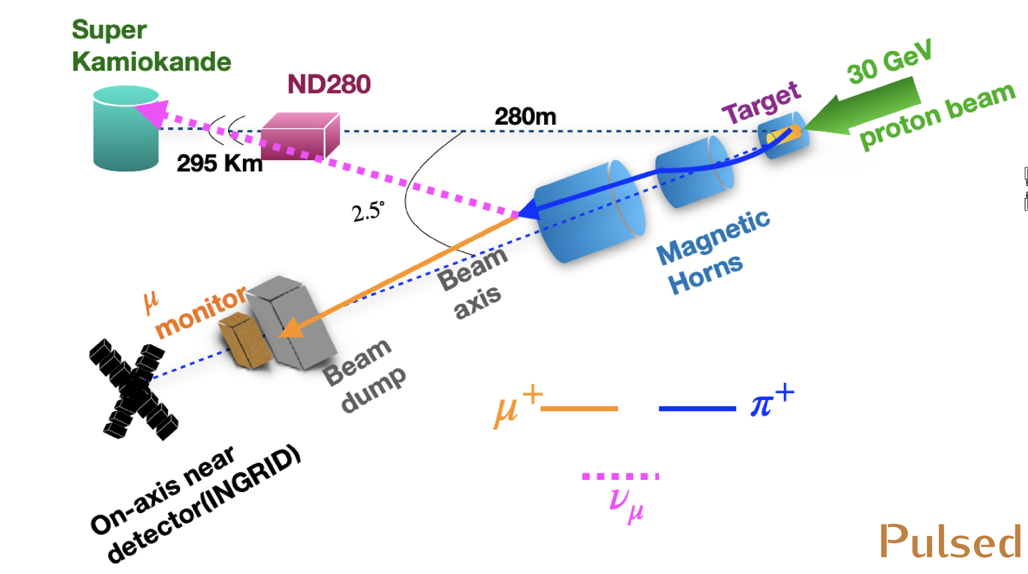
Neutrino flux prediction and corresponding uncertainties play an important role in oscillation parameter extractions and cross-section measurements [1].

T2K Neutrino Beam

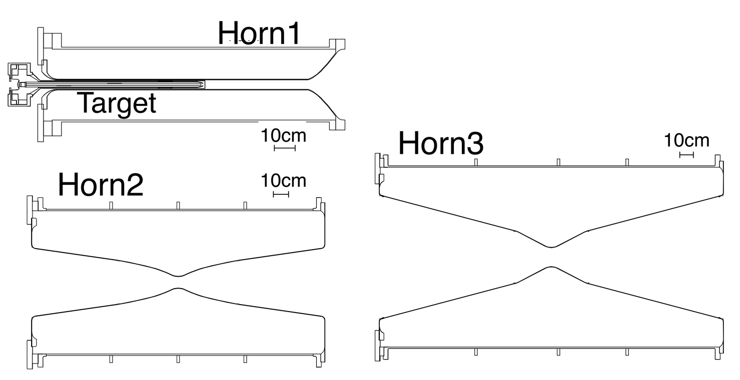
- T2K uses the off-axis (at 2.5°) technique to produce a narrow-band neutrino beam with peak energy at 600 MeV.
- A 30 GeV proton beam produced at the J-PARC facility impinges on a 90cm long graphite target.
- Secondary beam of $\pi^\pm$, $K^\pm$ are produced using three charge focusing magnetic horns.
- The secondary beam decays in a 96m long decay pipe to produce a narrow band neutrino beam.



Neutrino oscillation probability and flux as a function of neutrino energy.



Schematic of neutrino beam generation at T2K.



Pulsed horn current : 320kA(-320kA) for $\nu_\mu(\bar{\nu}_\mu)$ mode.

T2K Neutrino Flux Simulation Flowchart : JNUBEAM*

- Primary interactions within target and baffle using FLUKA [2] ← Proton beam profile measurements
- ↓ Interactions and tracking outside target using GEANT3 [3] ← secondary beamline configuration (e.g. Horn field measurements)
- ↓ Flux tuning ← External data of hadron production and cross-sections
- ↓ Flux prediction

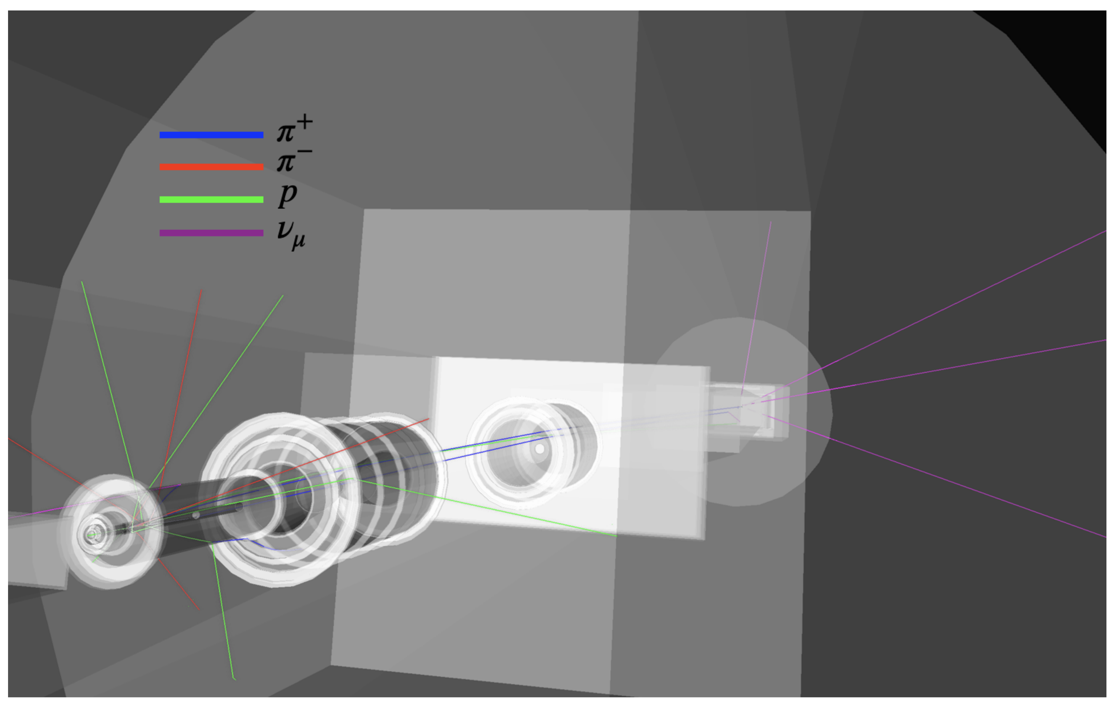
*The current neutrino flux prediction framework for T2K.

Shortcomings :

- Multiple software dependence.
- Physics models in GEANT3 are no longer maintained. ☹

GEANT4-based Framework : G4JNUBEAM

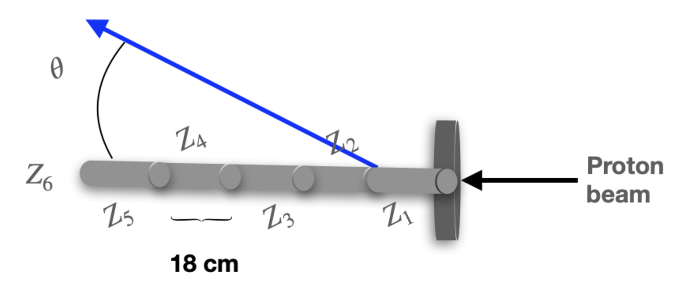
- A comprehensive framework relies on only GEANT4 toolkits [4] and their available physics models.
- Flexible geometry compatibility: GDML (Geometry Description Markup Language) format.
- Converted JNUBEAM (GEANT3) geometry to GDML.
- Physics processes considered for: (I) The primary proton hadron interactions inside the target. (II) Secondary hadronic interactions in and outside the target. (III) Subsequent weak decays of hadrons and muons to produce neutrinos.



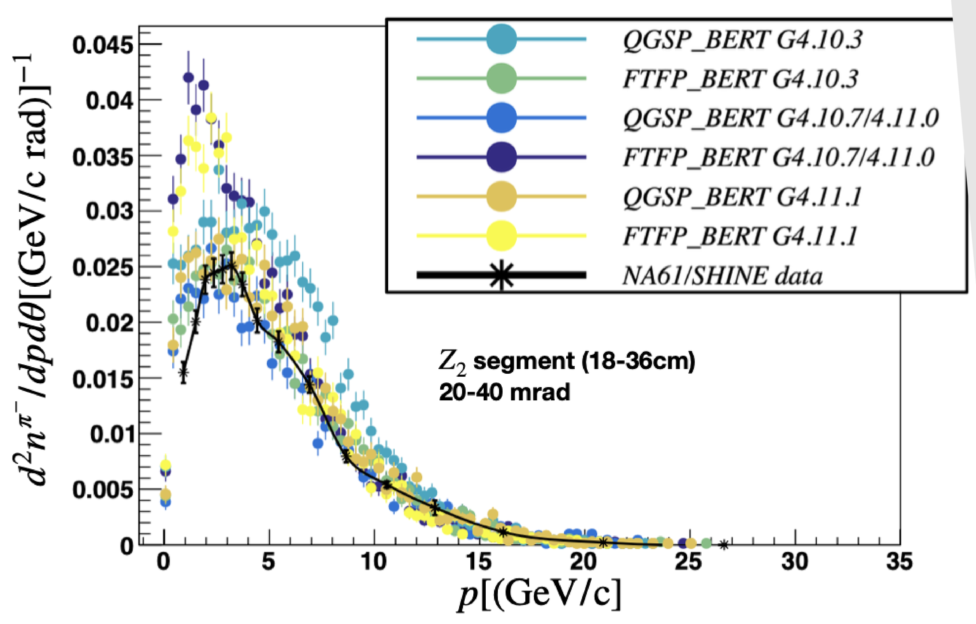
Event visualization in G4JNUBEAM.

Hadron Production From Replica Target

Differential yields of charged $\pi^\pm$, $K^\pm$ and p as a function of momentum and angle for six different segments are provided by the NA61/SHINE 2010 run [5].



T2K Replica Target at NA61/SHINE

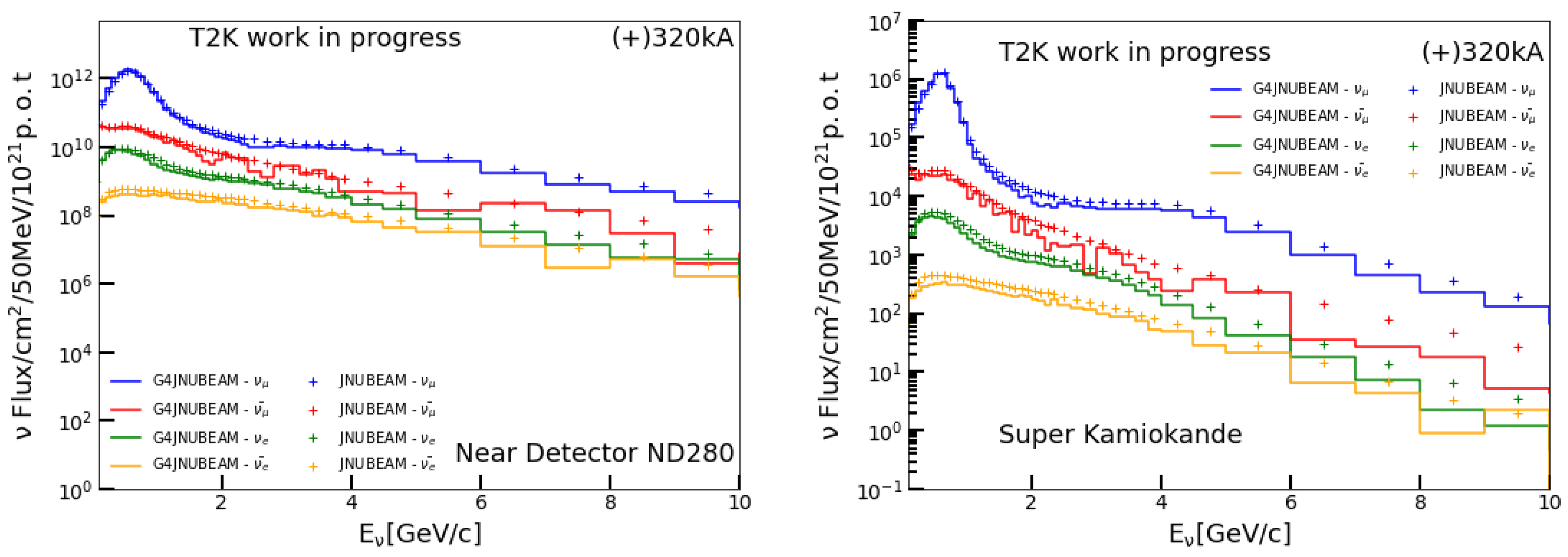


Benchmarking : The pion-yields from the GEANT4 framework (using T2K replica target and NA61/SHINE proton beam profile) are found to match the data well. The benchmarking is done using the QGST_BERT and FTFP_BERT physics models. ☺

Double differential π^- yields from replica target at NA61/SHINE and benchmarking using different physics models of GEANT4.

Neutrino Flux : G4JNUBEAM

- G4JNUBEAM (using FTFP_BERT physics model) shows good agreement with JNUBEAM, validations are in progress.
- The flux is ready to use for tuning with the NA61/SHINE hadron production data [5], the work is in progress.



Neutrino flux predictions at ND280 and Super Kamiokande using G4JNUBEAM.

The new neutrino flux prediction framework, G4JNUBEAM, will soon be used for the neutrino oscillation studies at T2K.

References: [1] K. Abe *et. al.*, Phys. Rev. D **87**, 012001 (2013), [2] G. Battistoni *et. al.*, Annals of Nuclear Energy **82**, 10-18 (2015), [3] R. Brun *et. al.*, **CERN-DD-EE-84-1**, [4] S. Agostinelli *et. al.*, Nucl. Instrum. Meth. A **506** 250-303 (2003), [5] N. Abgrall *et. al.*, Eur.Phys.J. C **79** (2019) no.2, 100.