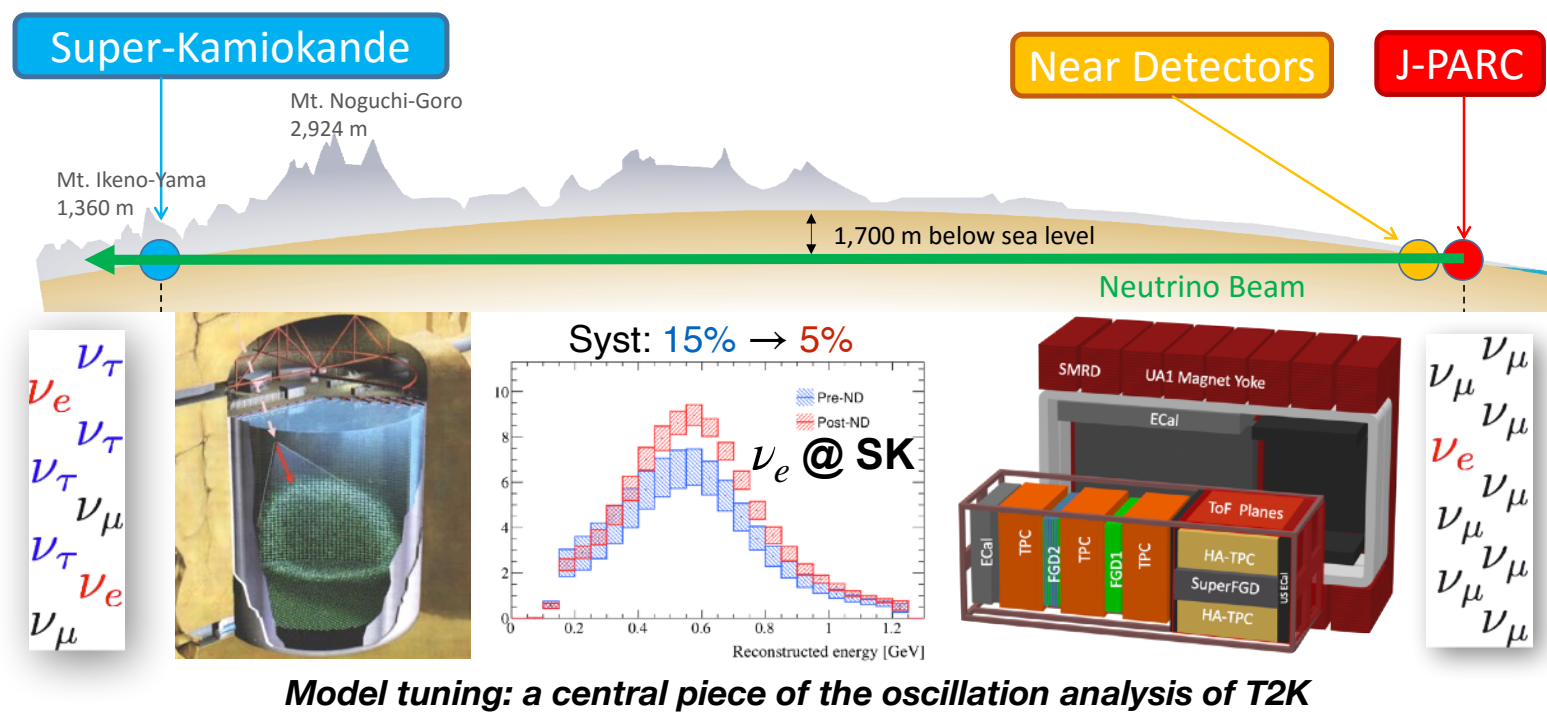


Long baseline neutrino experiments are moving toward precision measurements of the oscillation parameters; **namely the CP-violating phase, the mass ordering or the octant of θ_{23}** . This means systematic uncertainties must be reduced to few percent level, especially those related to neutrino interactions. This is usually done by using near detector (ND) data to constrain theoretical models.

The Japanese experiment Tokai to Kamioka (T2K) aims at measuring these parameters with neutrinos produced as a beam at J-PARC and detected in Super-Kamiokande [1]. As T2K is meant to be making precision measurements, **it is essential to have a sufficient understanding of the systematic uncertainties**. Therefore, T2K uses a set of near detectors called ND280 placed near the production site.

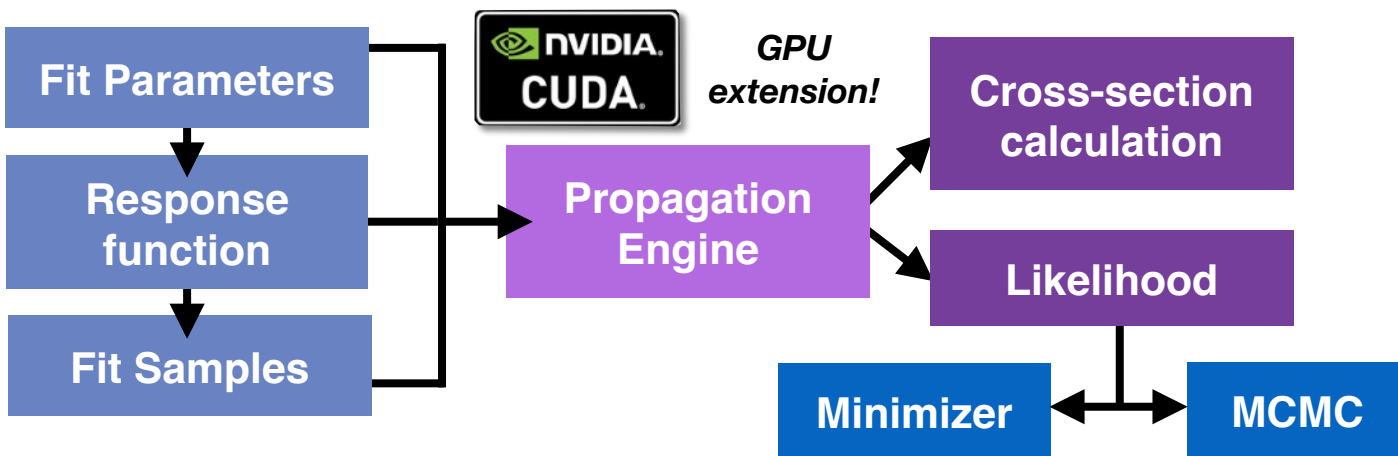
Performing a tuning of our neutrino flux and interaction model using measurements in the NDs involves **fitting few hundreds of nuisance parameters**. GUNDAM main purpose is to take care of this task.



A single code for statistical analyses of long-baseline experiments

GUNDAM (for **Generalized and Unified Neutrino Data Analysis Methods**) is a multipurpose ROOT-based fitter which aims at providing a common tool for oscillation and cross-section working groups of T2K.

The code structure has been designed for handling many different analyses. On one hand, **users can specify their own analysis using a set of YAML/JSON configuration files** which describes how GUNDAM need to load the data and perform the fit. Developers on the other hand focus on the code validation, optimisation and on the addition of new features so every user can benefit from it in the upcoming versions.



The heart of GUNDAM lies in an engine which propagate the effect of our model parameter to the fitted samples. Thanks to the HEMI library, **the same code can be ran on either CPU or GPU with Nvidia CUDA**. Additional modules are taking advantage of the propagation engine, such likelihood calculation or cross-section calculator tool.

The likelihood module is used for fitting parameters. **The embedded Minimiser uses MIGRAD/HESSE algorithms of Minuit2**. Additionally an independent MCMC enchain can be used for performing a bayesian analysis.

Build your own analysis with GUNDAM

Define your samples → Define your parameters → Many data formats supported

SCAN ME

CCQE parameters

FHC FGD1 ν_μ CC 0p 0p 0y

Monitoring gradient descent

- Work with various input formats
- Define custom binning with multiple variables
- Define any samples and fit parameters with simple string expressions
- Perform fits with multiple datasets (multiple detectors / combined analyses)
- Option to use Eigen space for highly correlated parameters
- Principal Component Analysis based on the impact of parameter on the likelihood
- Extensive diagnostic figure generator: parameter scanning, drawing any sample variables
- Toy generation with prior covariance matrices and coverage studies

GUNDAM has been **largely validated against the previous results of T2K** oscillation analysis performed by the BANFF software tool! [2]

GUNDAM can **produce several outputs allowing users to check and debug their analyses**:

- Post-fit central values and errors
- Covariance matrices
- Event TTree with associated weights
- Parameters scans - likelihoods, bin content
- Event rates breakdown
- Advanced decomposition of the Hessian matrix
- Event-by-event dials in the output file

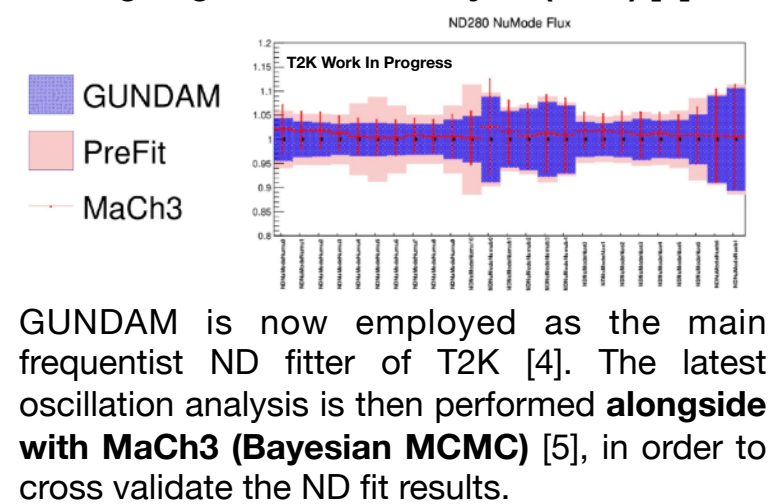
A few key features for your analysis

- Sample definition with arbitrary binning and cuts
- Define fit parameters with a constraint or free and provide a covariance matrix
- Event-by-event or binned response functions
- Define response functions with either norm, graph, splines, ROOT formula or pre-compiled functions
- Variable definitions with string expressions or pre-compiled code on runtime
- Post-fit model extraction (used for cross-section analyses)
- NEW: multi-parameter response functions like oscillation probability. For instance:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2(\Delta m^2 L/E)$$

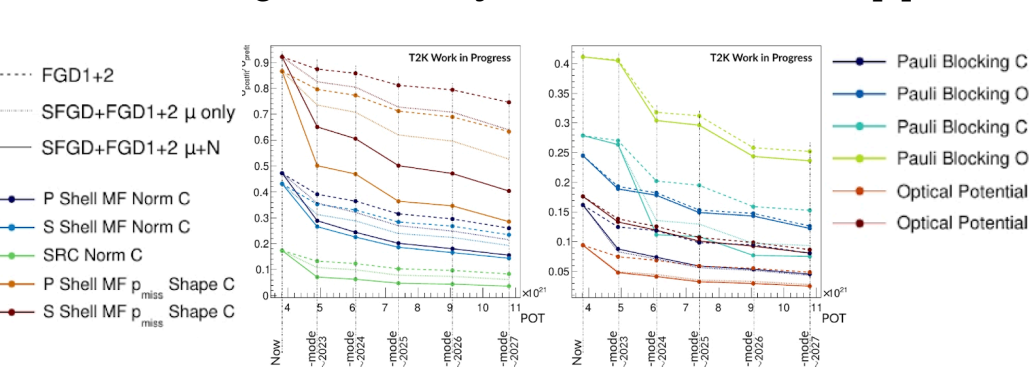
An open-source tool widely used in T2K

Ongoing oscillation analysis (2024) [3]



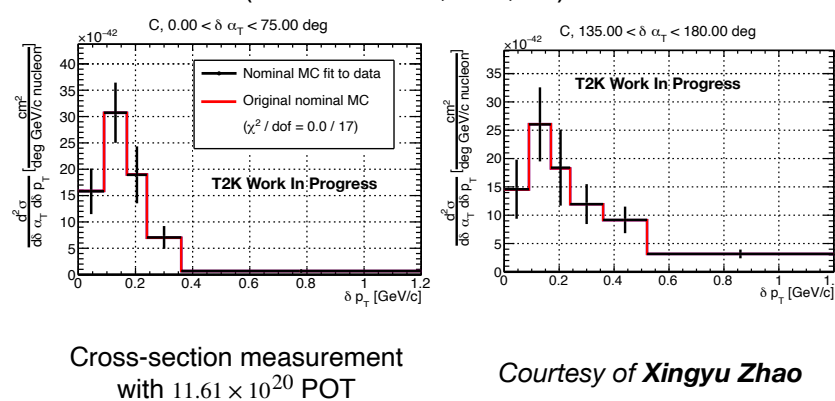
Sensitivity studies with the Upgraded ND280 [6]

Based on the current Protons-On-Target (POT) projections, GUNDAM was used to evaluate the **impact of the ND Upgrade on constraining the CCQE systematic uncertainties** [7].



Post-fit differential cross-section calculation

Transverse momentum imbalance δp_T allows to probe nuclear effects (Fermi motion, FSI, ...).



[1] Eur.Phys.J.C 83 (2023) 9, 782
[2] 10.5281/zenodo.6683820
[3] See plenary talk of Claudio Giganti
[4] See poster of Léna Osu

[5] See poster of Ewan Miller
[6] arXiv:1901.03750
[7] 10.5281/zenodo.6766990