WP2.3: Neutrino-Nucleus interactions

Task 2.3: Neutrinos cross section measurement

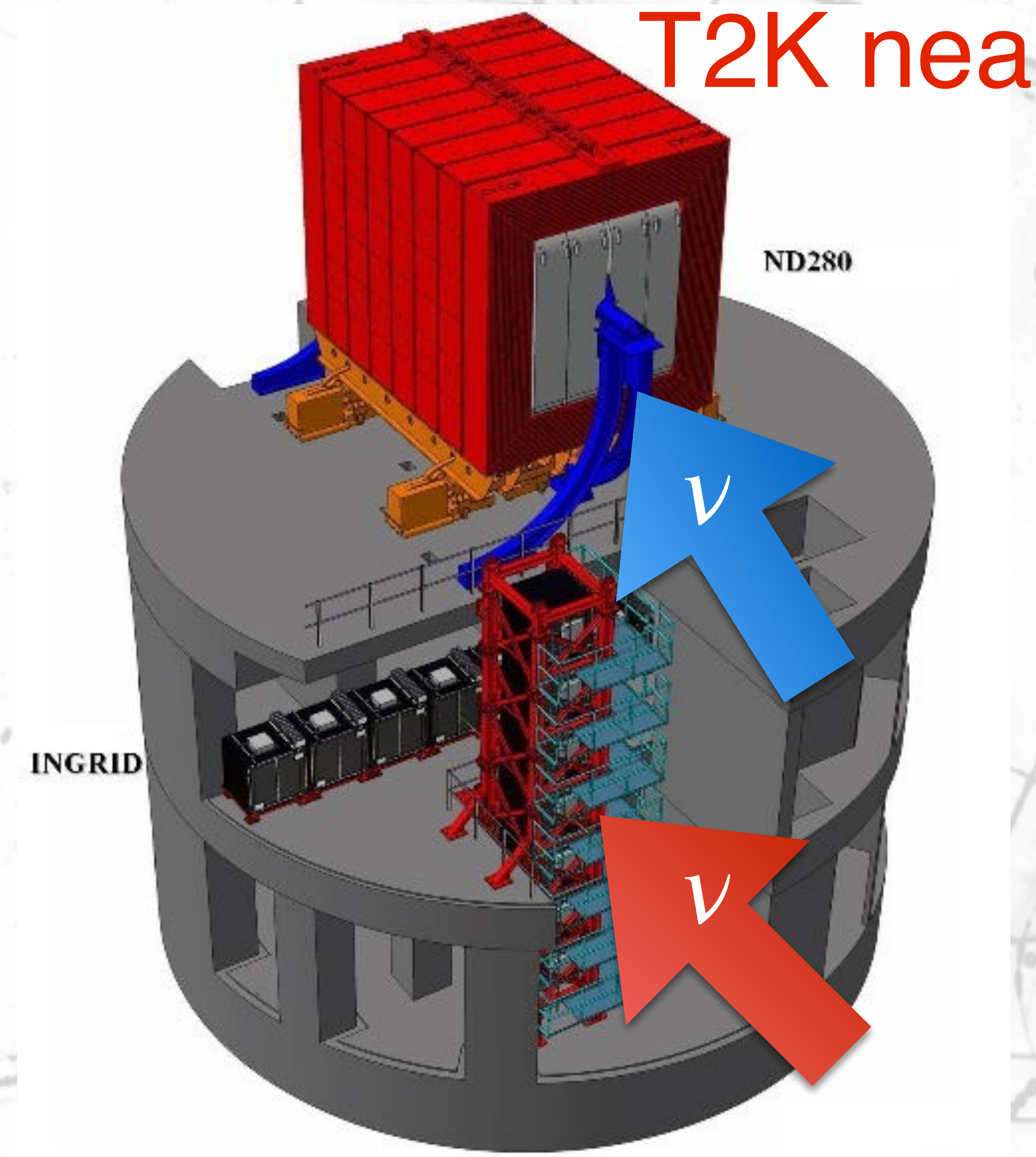
- This task is an excellent playground for a broad community of theoreticians and experimentalists, mixing different skills and backgrounds. It is also a valuable environment for students, where they can enrich the foundations of their career. Cross-section of the different neutrino types on different targets (C, O, Fe) will be published open access and will be accompanied by public data releases in order to allow a broader community to interpret and study them.

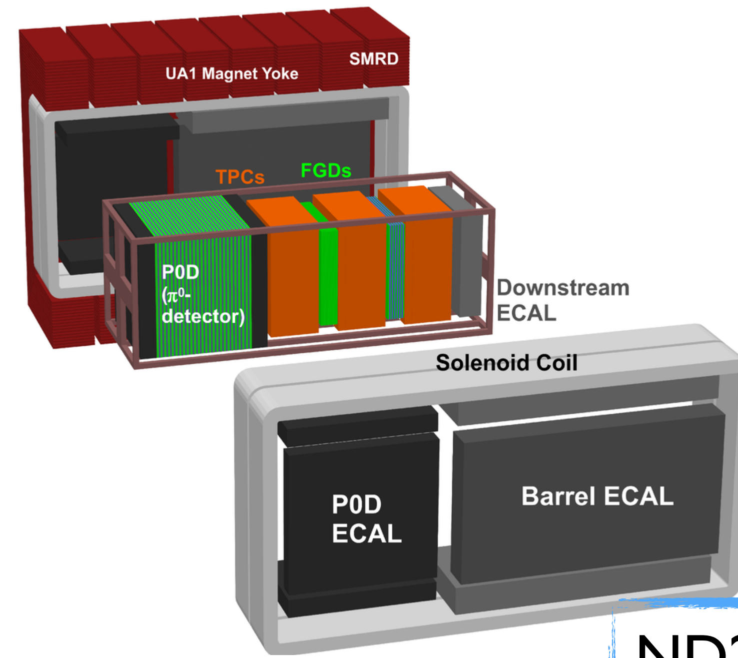
T2K Analysis

First measurement of muon-neutrino CC interactions without pions in the final state using multiple correlated energy spectra at T2K

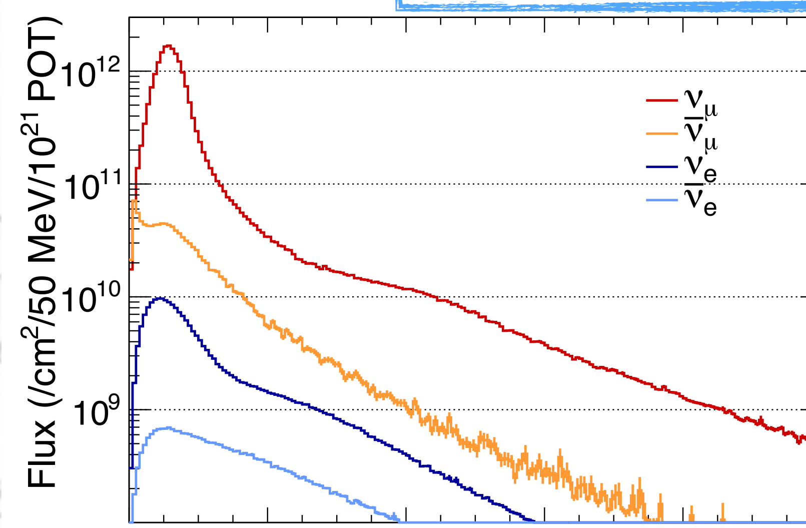
INFN, CEA, CNRS and UNIGE

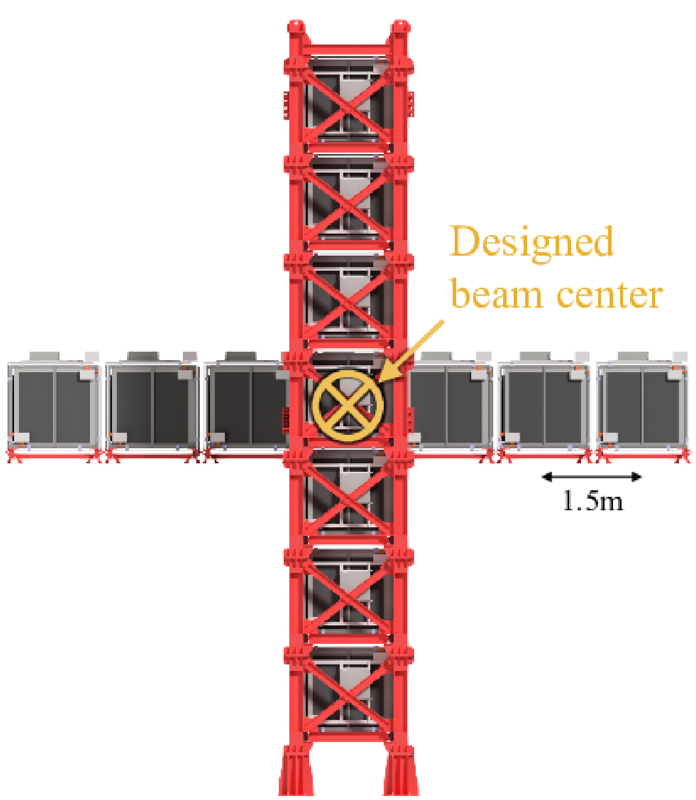
T2K near detectors and ν fluxes

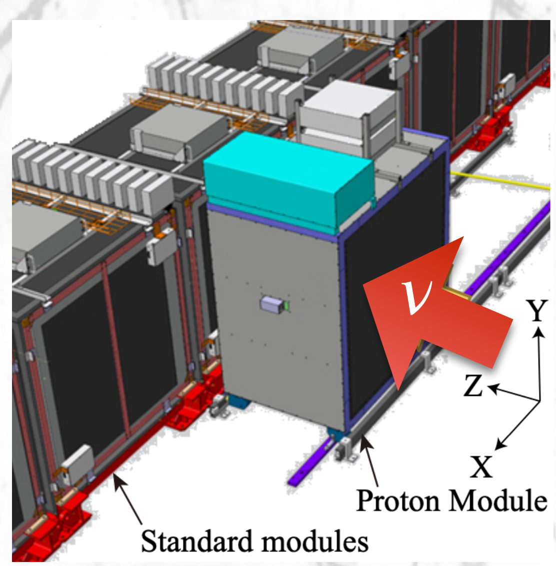




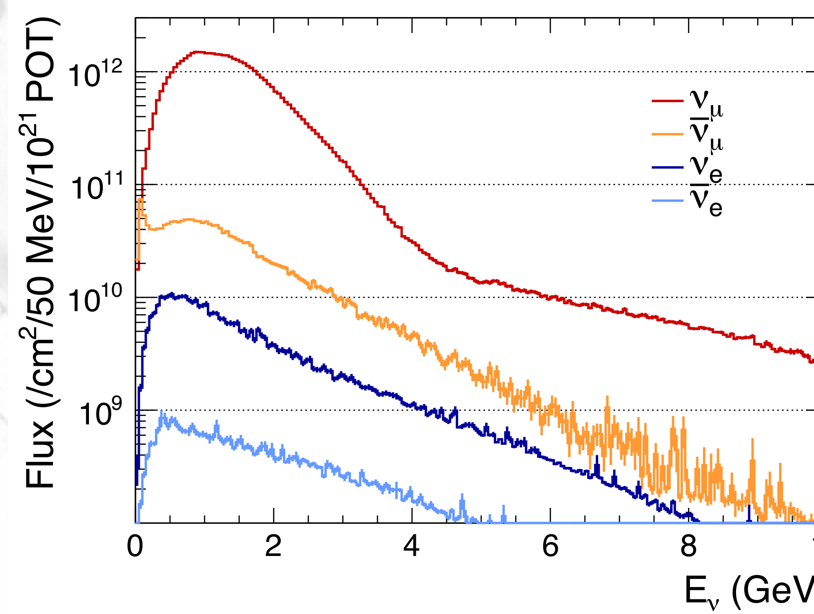
ND280 off-axis



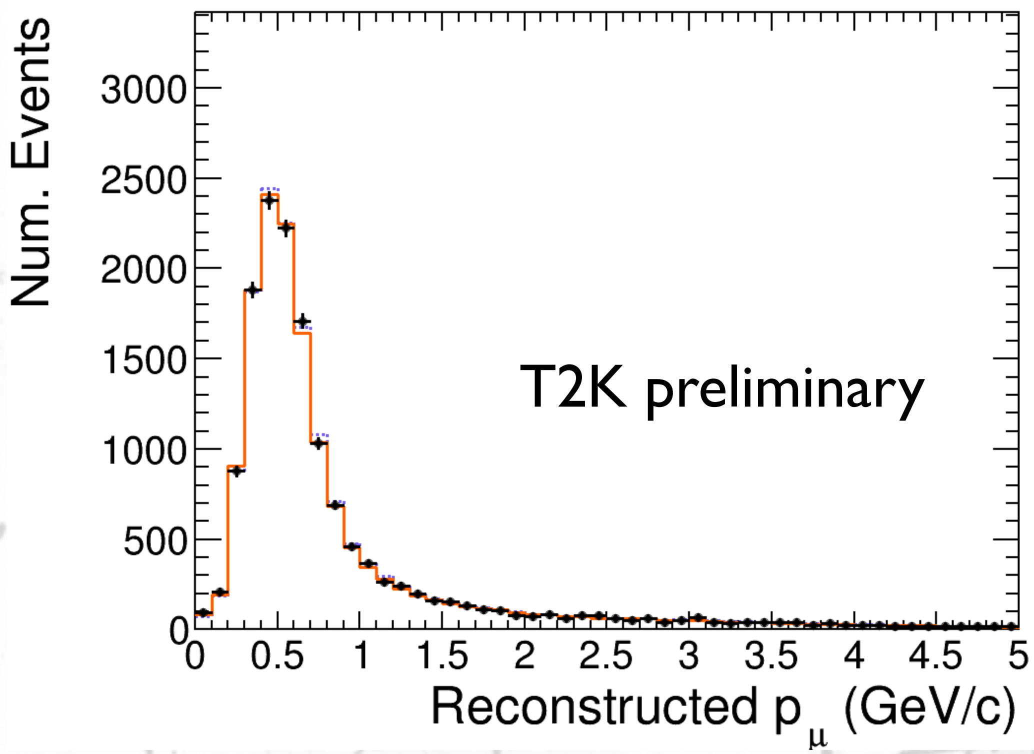


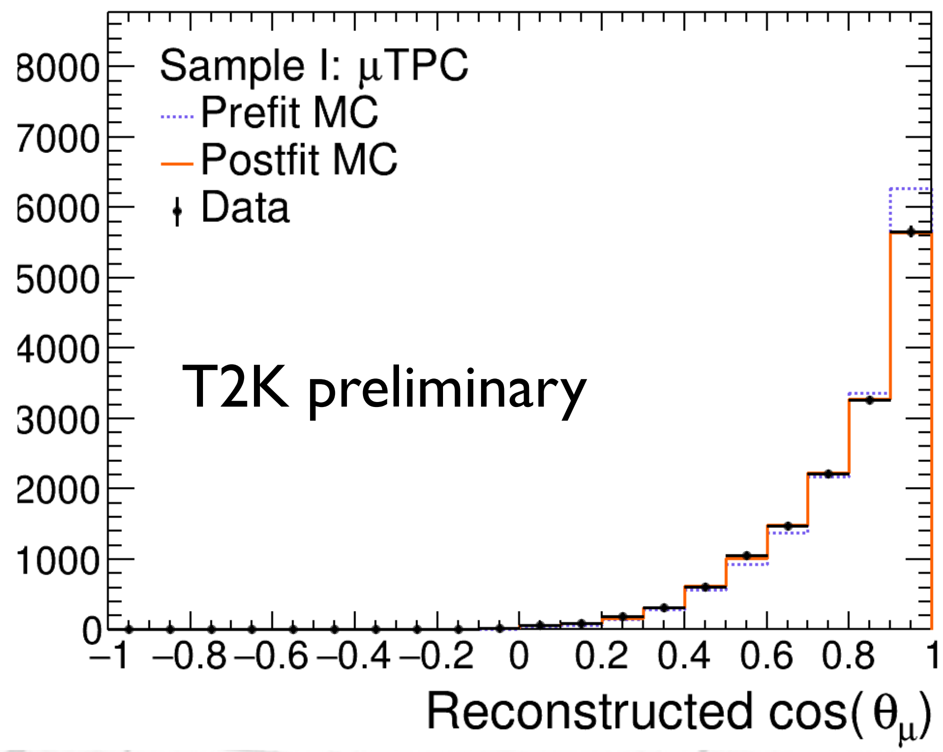


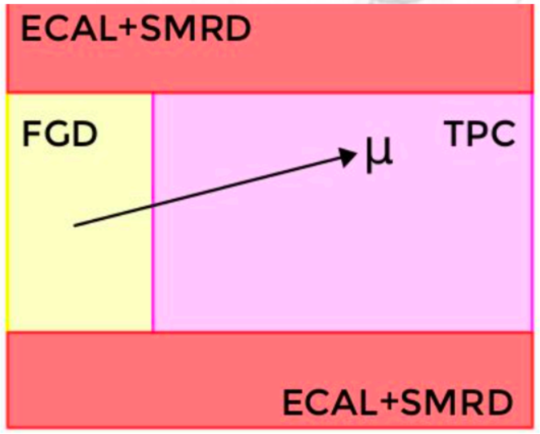
INGRID
on-axis

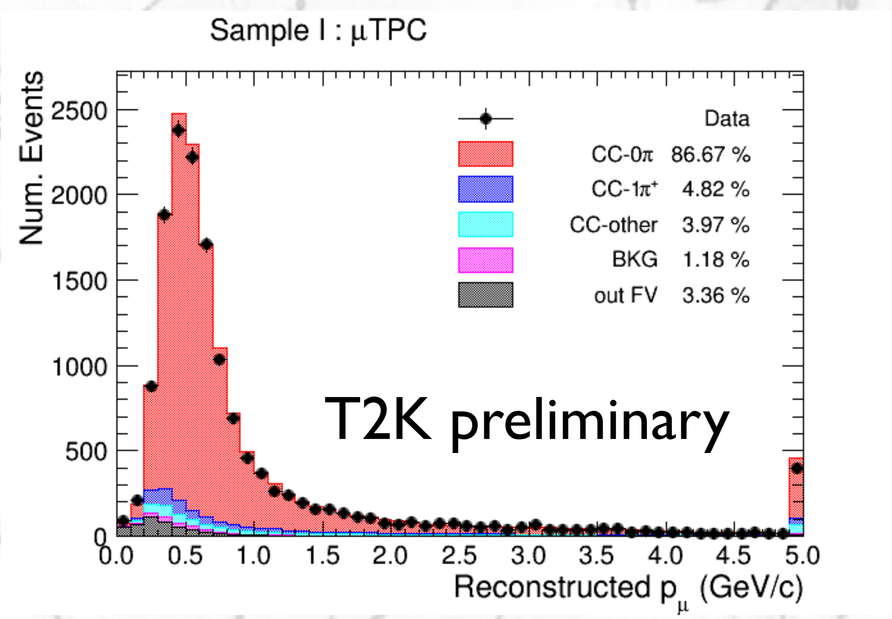


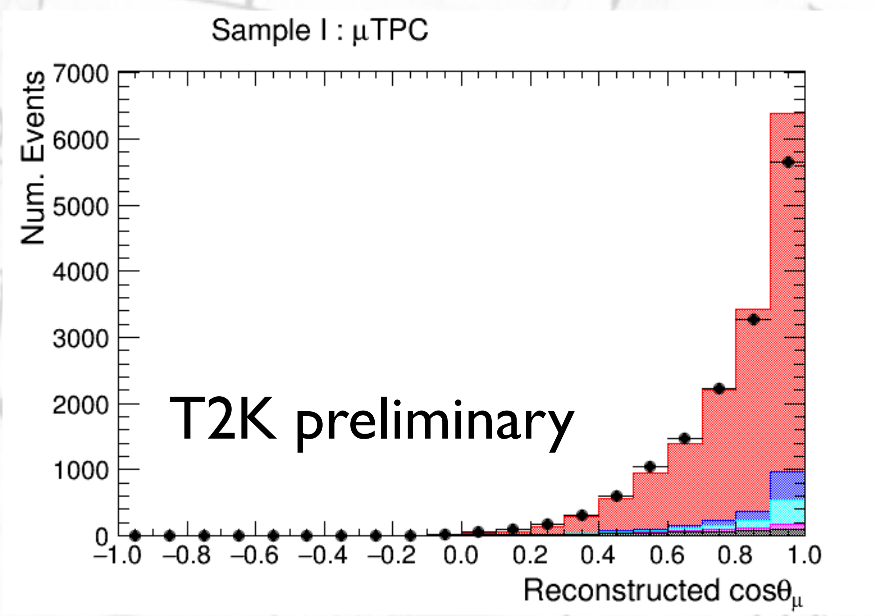
On-/Off-Axis Selection





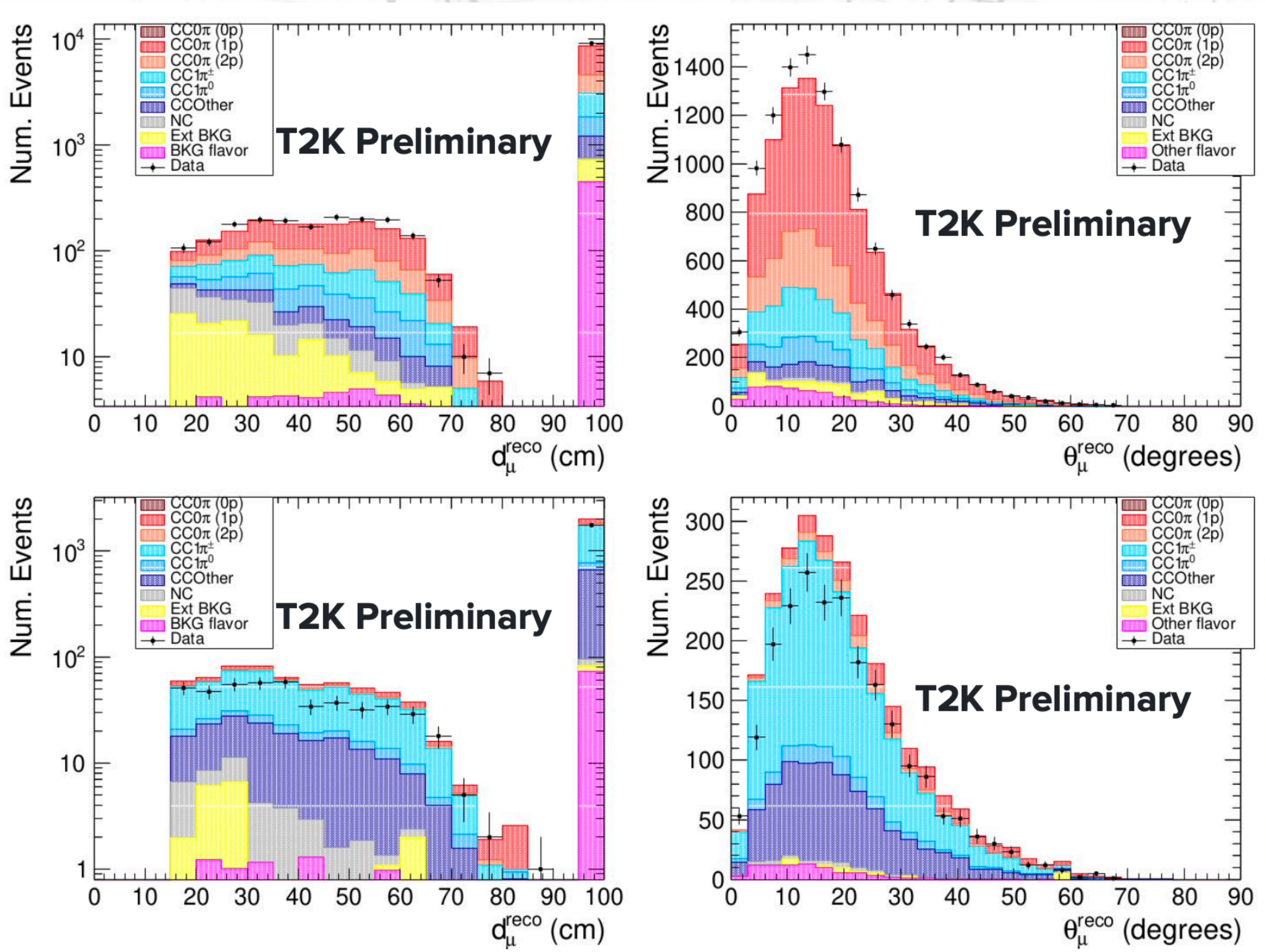


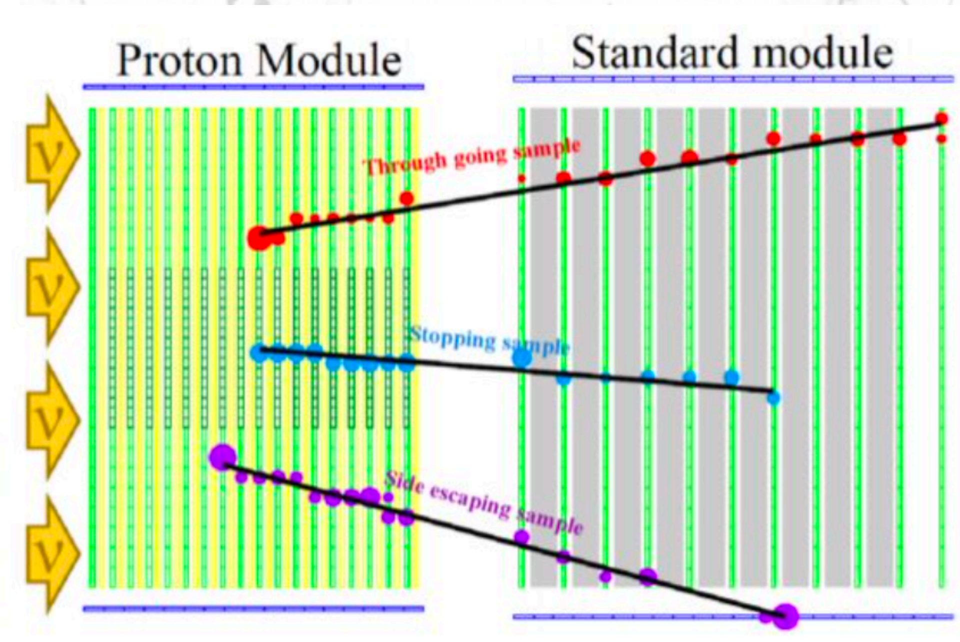




- Example of an ND280 signal sample showing the reconstructed muon momentum and cos(angle).
- This sample requires a muon to reach the TPC and no other detected particles, and is the largest sample.
- Colored histogram shows the nominal MC prediction separated by topology with the measured data overlaid.

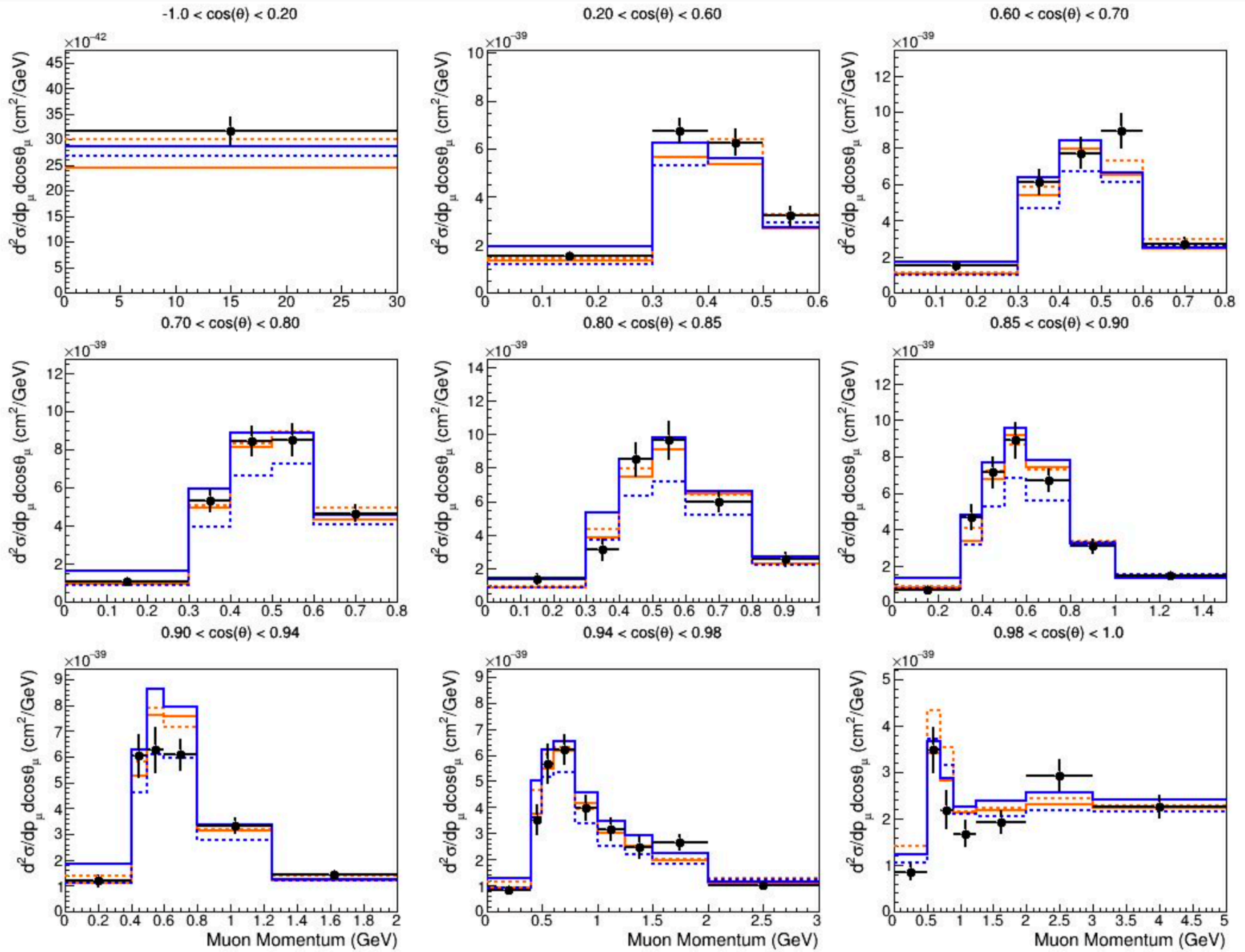
On-Axis INGRID Selection

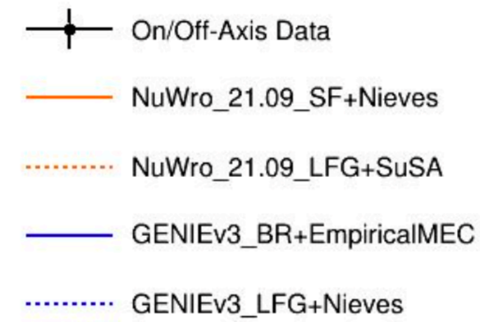




- INGRID through-going and stopping samples.
- CC0π samples on top, CC1π+ samples on bottom.
- The last bin for the distance plots contains all through-going events.

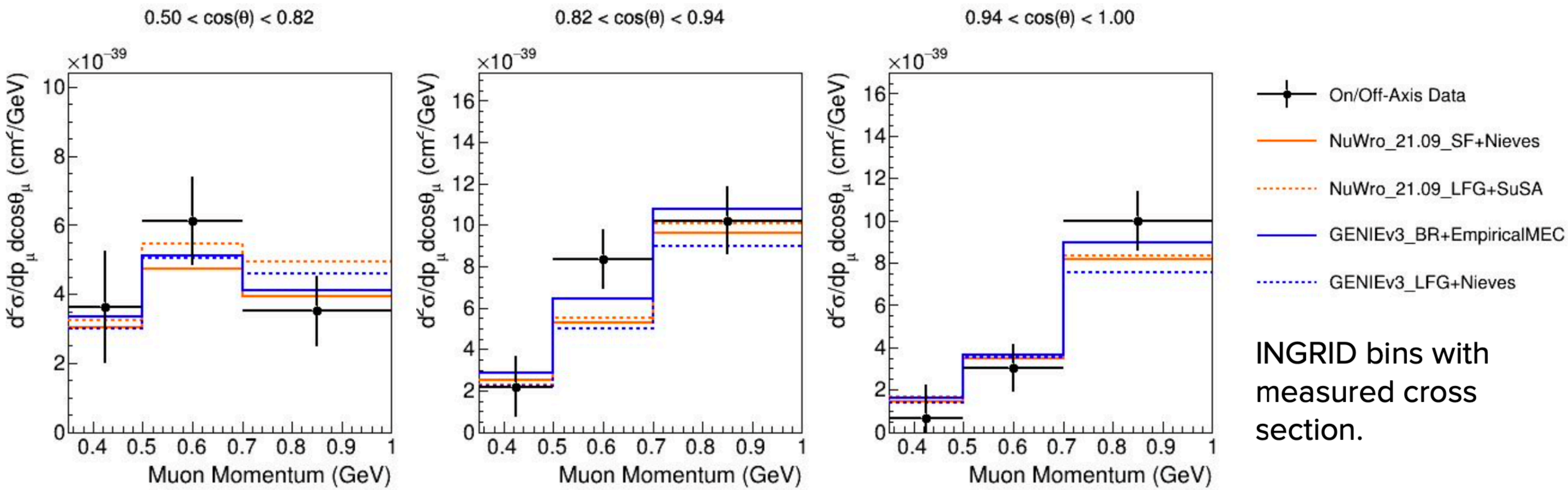
Off-Axis results





ND280 bins with measured cross section.

On-Axis results



INGRID bins with measured cross section.

Paper in preparation!

Target journal: **PRD**

Advanced analysis

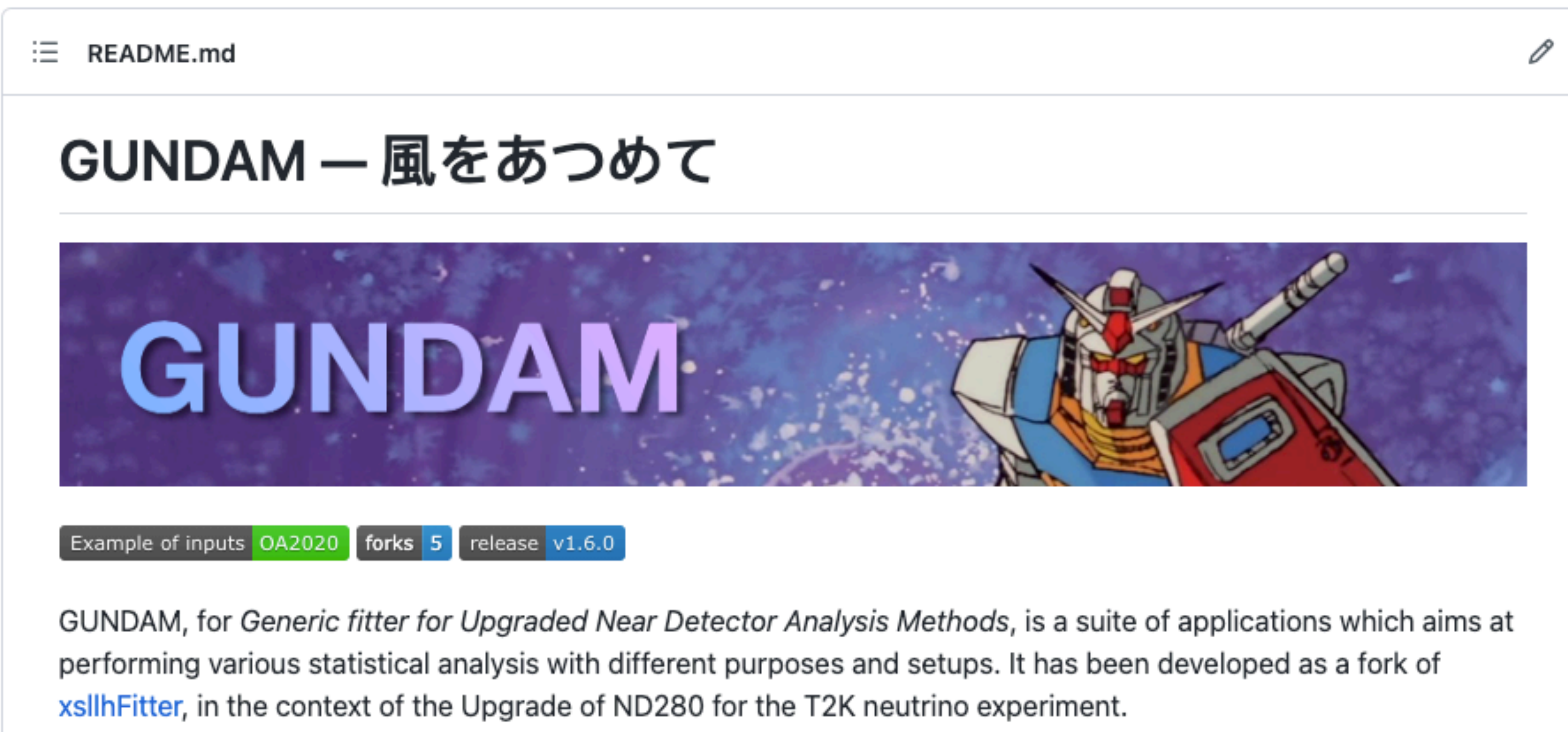
1. *anti-$\boldsymbol{\nu}_\mu$ CC1$\boldsymbol{\pi}^-$ analysis in FGD1* (G. Zarnecki).
2. $\boldsymbol{\nu}_\mu$ CC1$\boldsymbol{\pi}^+$ analysis in FGD1/FGD2 (S. Jenkins).
3. *NC1$\boldsymbol{\pi}^+$ analysis* (C. Jesus Valls).
4. *$\boldsymbol{\nu}_\mu$ CC0$\boldsymbol{\pi}$ analysis in WAGASCI/BM* (K.Yasutome).
5. Joint CC0$\boldsymbol{\pi}$ $\boldsymbol{\nu}_\mu$/anti-$\boldsymbol{\nu}_\mu$ on/off-axis (C. Schloesser).
6. *Kaon production analysis* (K. Kowalik).
7. 4$\boldsymbol{\pi}$ $\boldsymbol{\nu}_\mu$ CC1$\boldsymbol{\pi}^+$ analysis (D. Vargas, back!).
8. *anti-$\boldsymbol{\nu}_\mu$ CC1$\boldsymbol{\pi}^-$ analysis in FGD1*/FGD2 (L. O'Sullivan).
9. *$\boldsymbol{\nu}_e$ CC1$\boldsymbol{\pi}^+$ analysis in FGD1* (N. Latham).
10. *NC$\boldsymbol{\pi}^0$ in the P0D* (S. Liu).
11. *CC0$\boldsymbol{\pi}$ with Eavail analysis* (T.Vladislavjevic & K.Lachner).

New development in this context: GUNDAM

IN2P3
+
Saclay

GUNDAM: Generic fitter for Upgraded Near Detector Analysis Methods

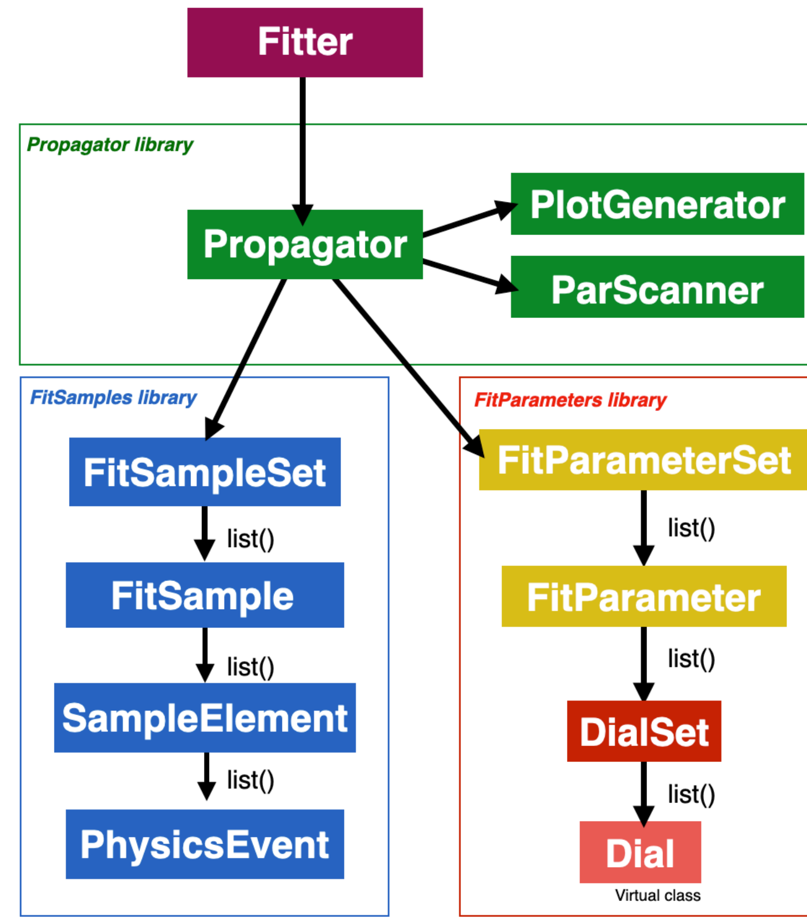
- Fitter framework for the next statistical analysis of T2K
- Framework designed to host multiple analysis using **JSON/YAML configuration files**
- Open source (LGPL) C++ code based on ROOT publicly available on GitHub


README.md

GUNDAM — 風をあつめて

Example of inputs OA2020 | forks 5 | release v1.6.0

GUNDAM, for *Generic fitter for Upgraded Near Detector Analysis Methods*, is a suite of applications which aims at performing various statistical analysis with different purposes and setups. It has been developed as a fork of xsllhFitter, in the context of the Upgrade of ND280 for the T2K neutrino experiment.



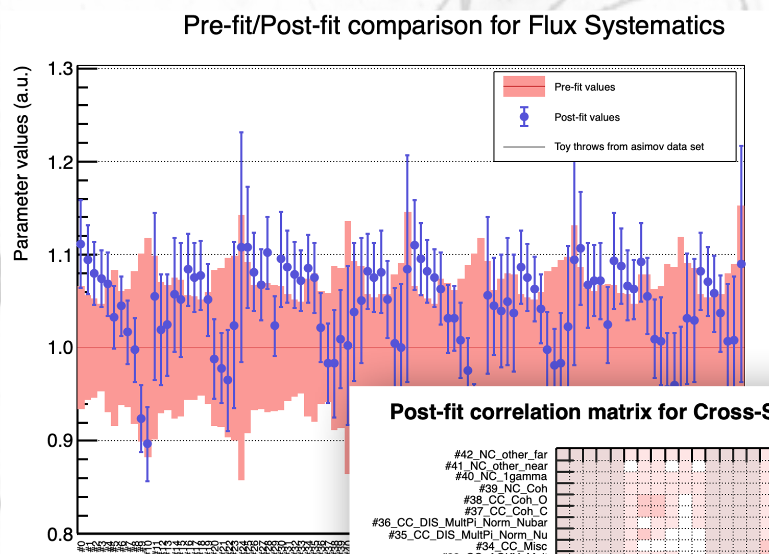
A new way of performing statistical analysis

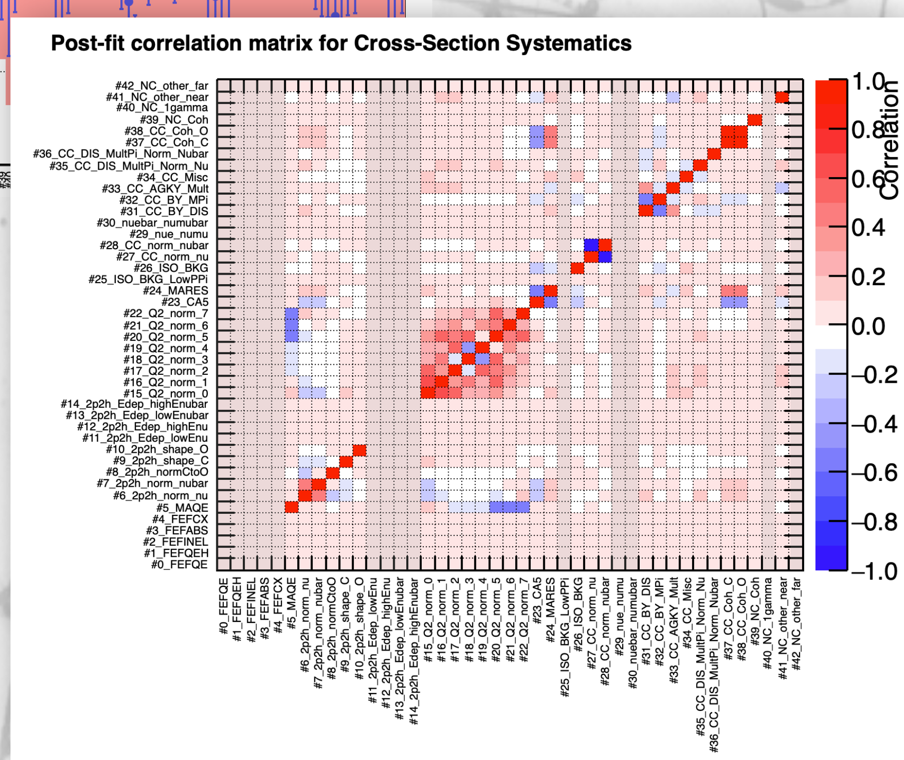
- Separate fitter development works from analysis developing works
- Better traceability and validation of the output → share inputs easily with other people

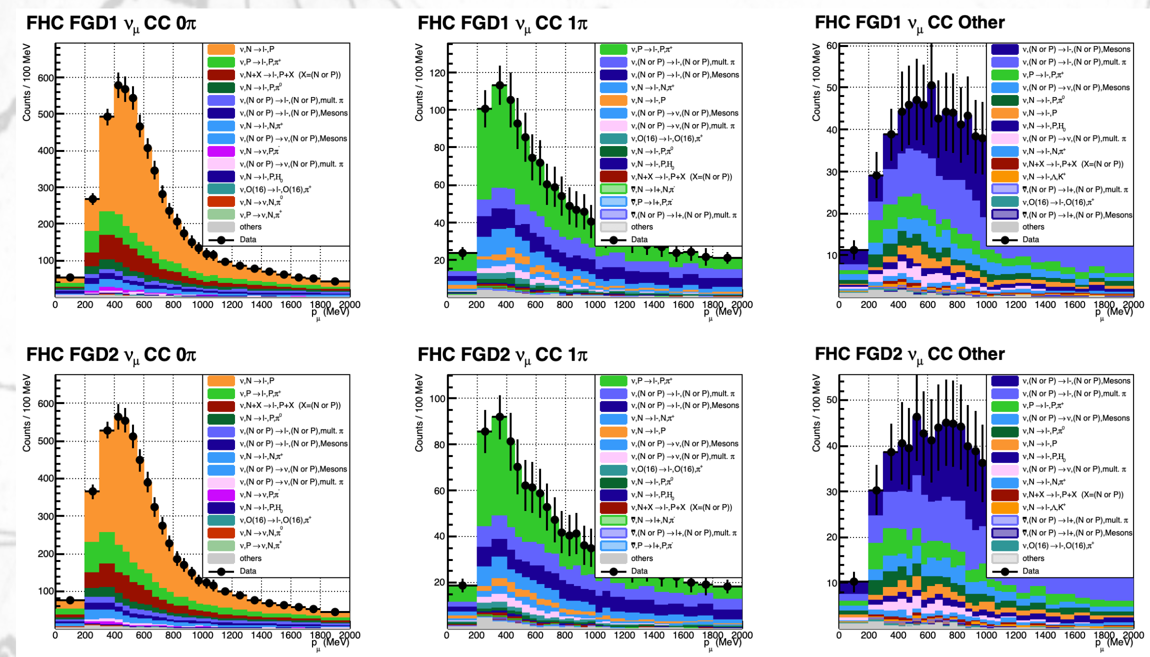
Auto-generated outputs

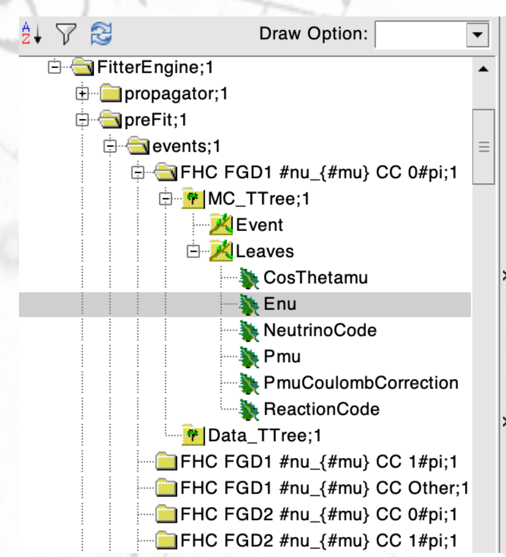
Configurable figures and data generator in the output ROOT file

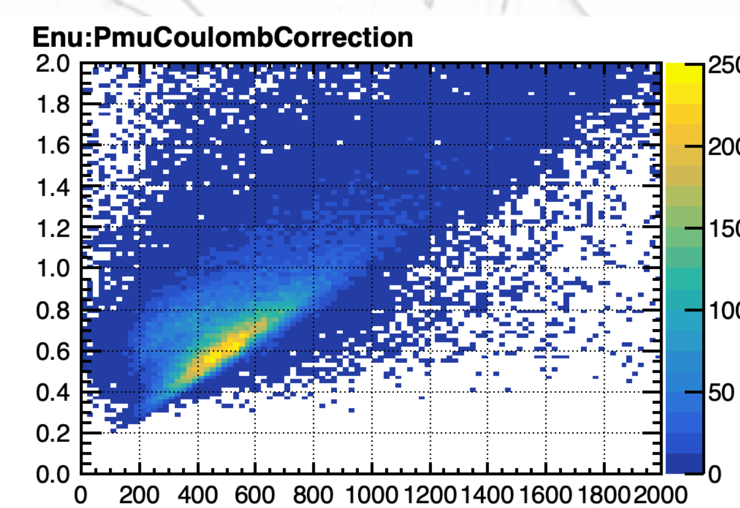
- Debug info (command line, full JSON configuration, GUNDAM version…)
- Fit histograms / projection on a given variable / breakdowns
- Likelihood parameter scans
- Event rate monitoring wrt parameter variations
- Loaded sample events data in TTree
- Post-fit values, error, covariance, hessian decomposition



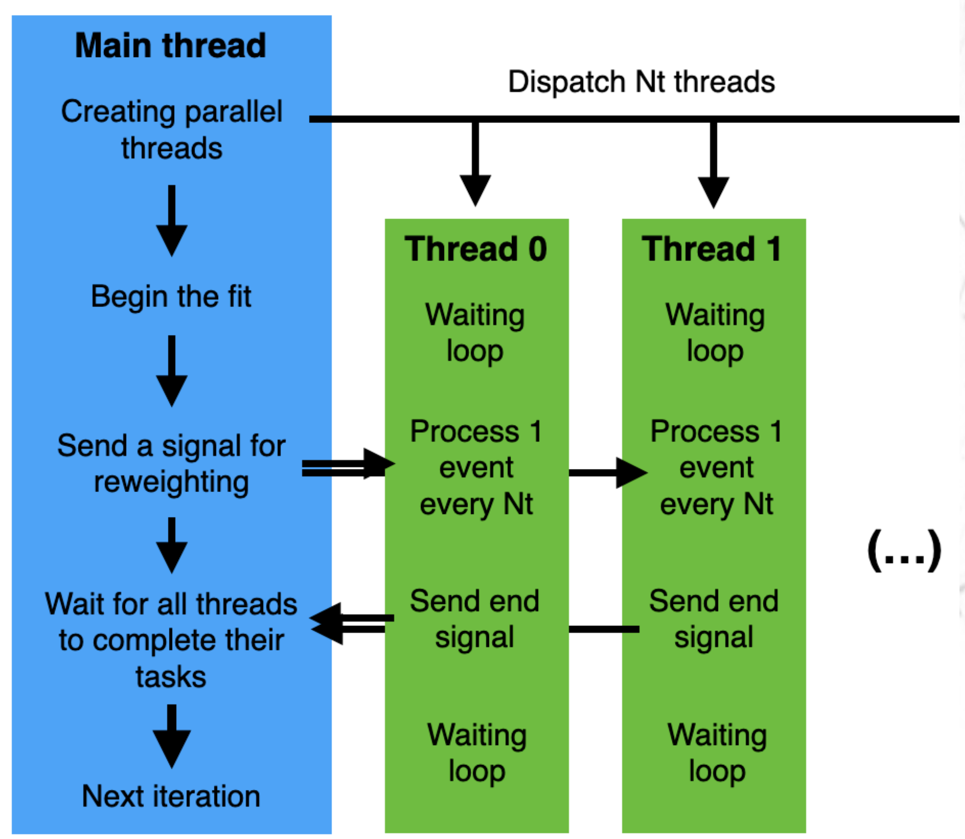








Optimisation: parallelising tasks



Parameter propagation is fully parallelised using CPU thread workers

- Main thread sends a signal to the parallel threads
- Each thread propagate the systematics on a subset of events
- Near 100% CPU efficiency (depending on the RAM access speed)

Expanding to GPU computing

- Unified CPU/GPU dial computation (same actual C++ code)
- Highly optimised cache system
- Optimising the amount of memory involved during the fit (T2K OA ~24GB in RAM)

Stony Brook University

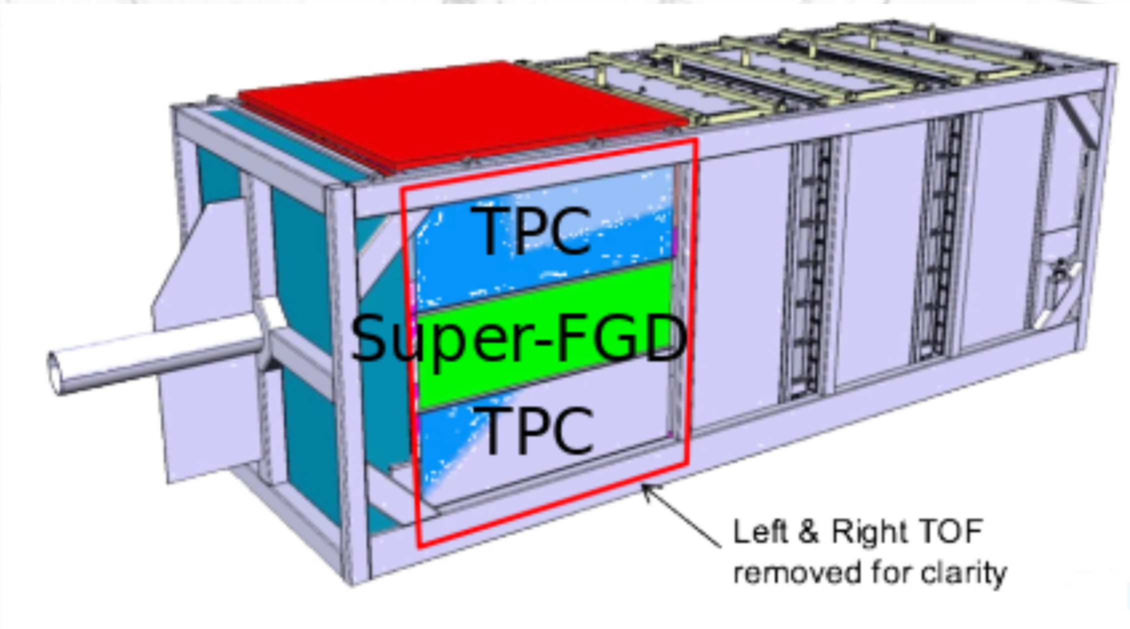
NVIDIA CUDA

	1 Thread	16 Threads
CPU (standard GUNDAM)		7.63 it/s
GPU (only splines)		7.24 it/s
GPU (only event weights)	24 it/s (41 ms/it)	52 it/s (19 ms/it)
GPU (fill histograms)		64.6 it/s
GPU (fill histograms)		63.8 it/s

~8x faster on the T2K oscillation analysis fit

Upgrade

- Concentrating on the reconstruction and MC based analyses.
- Many analyses would be redone with the new (more performing) detector.



X-sect theory papers from within Jennifer

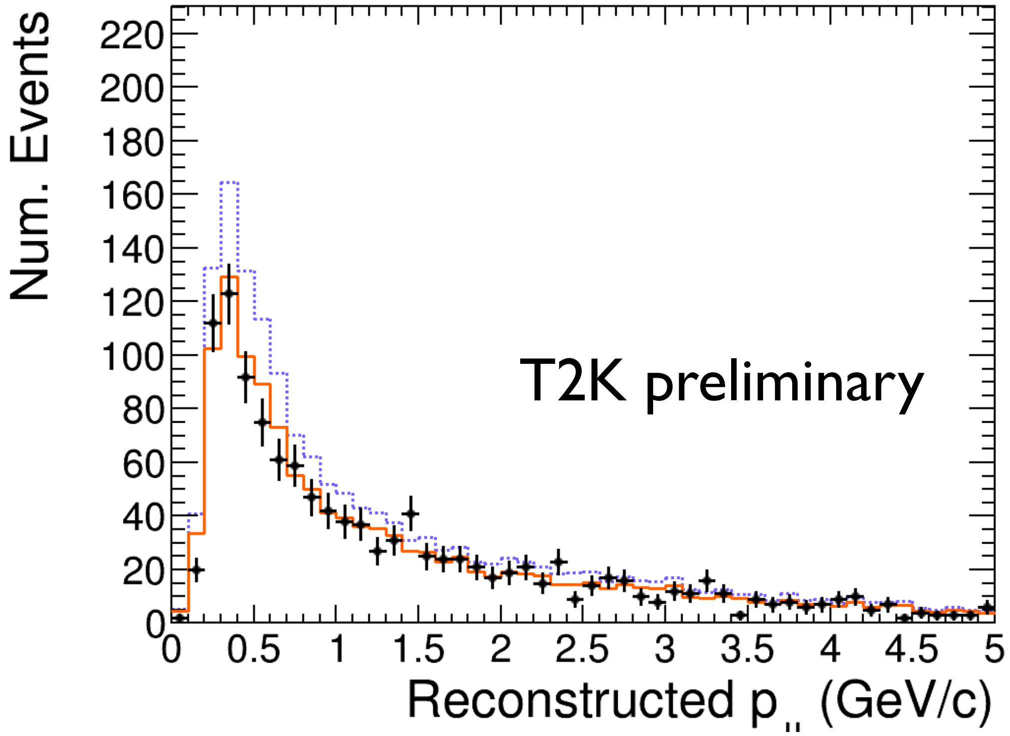
Probably not exhaustive

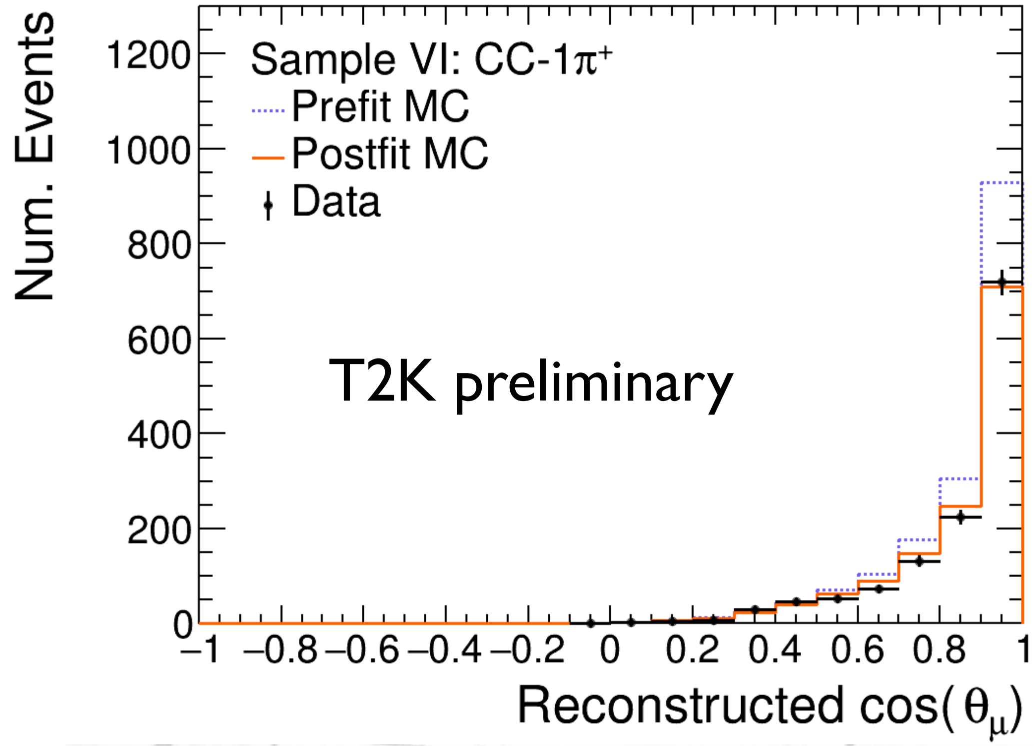
1. Sensitivity of Neutrino-Nucleus Interaction Measurements to 2p2h Excitations, (IRFU, Saclay)
2. Study of final-state interactions of protons in neutrino-nucleus scattering with INCL and NuWro cascade models (IRFU, Saclay)
3. Sensitivity of the upgraded T2K Near Detector to constrain neutrino and antineutrino interactions with no mesons in the final state by exploiting nucleon-lepton correlations. (IRFU, Saclay)
4. Inclusive and exclusive neutrino-nucleus cross sections and the reconstruction of the interaction kinematics (Geneva Univ.) (IFAE)
5. Exclusive final state hadron observables from neutrino-nucleus multi-nucleon knockout. (Geneva Univ.)
6. Tau longitudinal and transverse polarizations from visible kinematics in (anti-)neutrino nucleus scattering. (Geneva Univ.)
7. Benchmarking intranuclear cascade models for neutrino scattering with relativistic optical potentials. (Geneva Univ.)

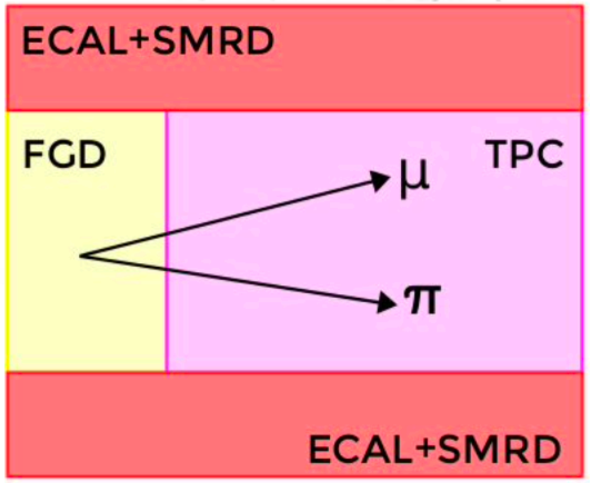
Many of these developments are going to be integrated in the official T2K MC and for the preparation of T2K new running period.

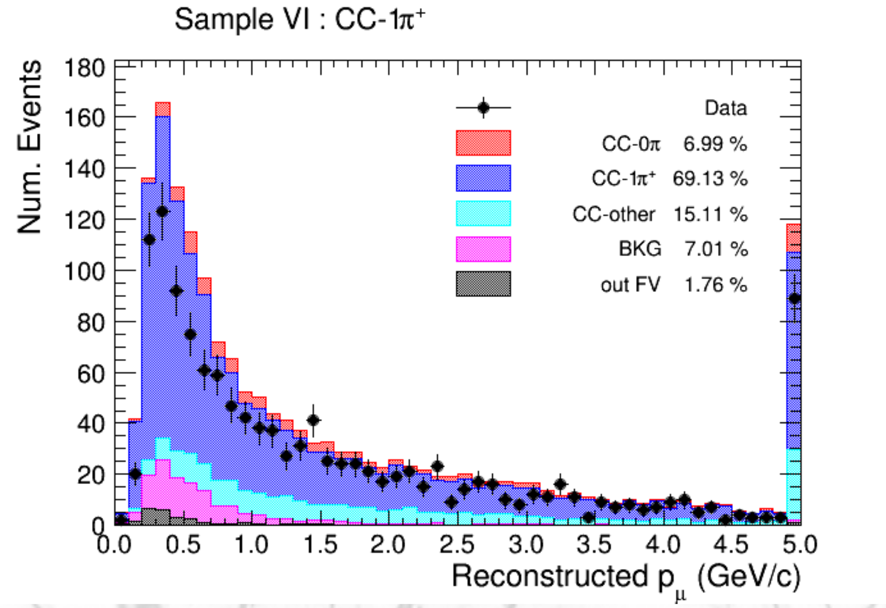
Support

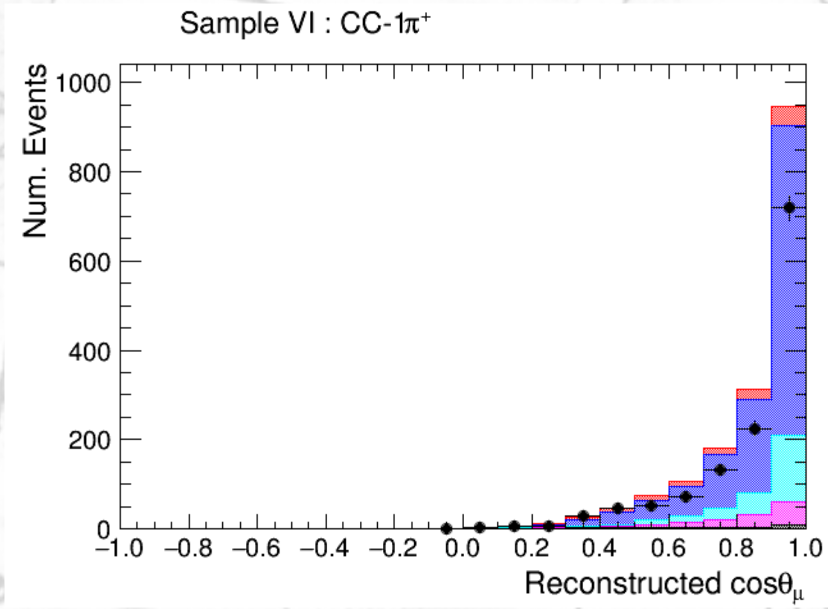
On-/Off-Axis Selection







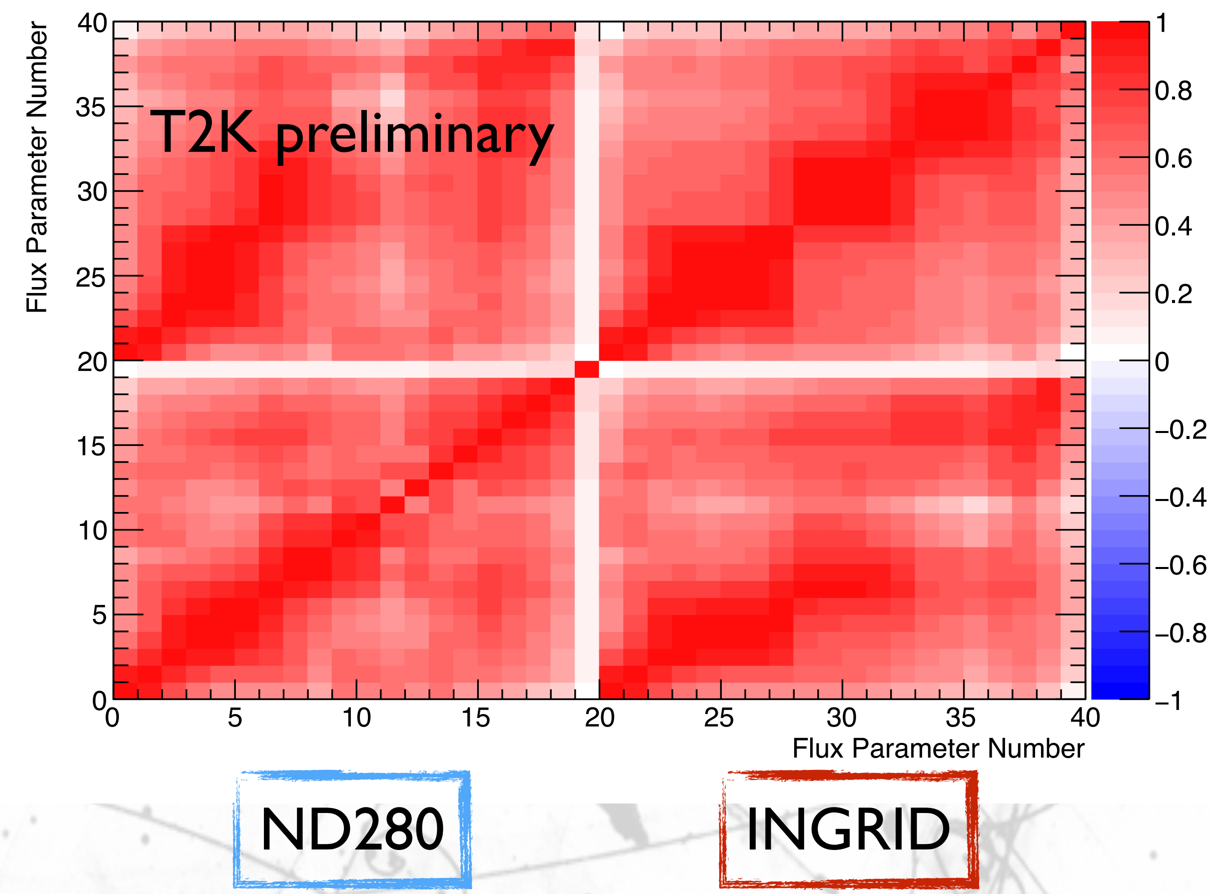


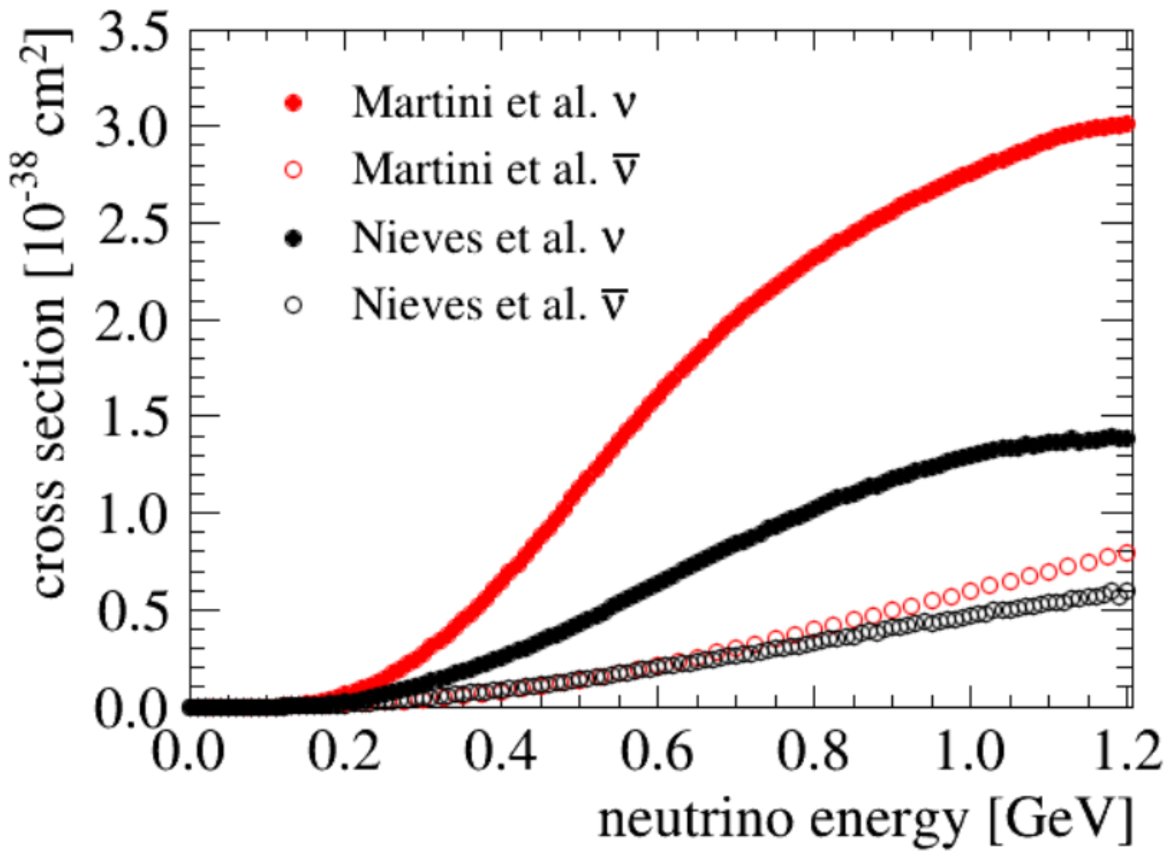


- Example of an ND280 control sample showing the reconstructed muon momentum and cosθ.
- This sample requires a muon and charged pion to reach the TPC with no other detected particles.
- Colored histogram shows the nominal MC prediction separated by topology with the measured data overlaid.

On-/off axis analysis

- **Simultaneous fit** using data from both **ND280** and **INGRID**.
- On-/off-axis positions result in different, but **highly correlated**, neutrino flux spectra.
- Provides an **opportunity** to **break** some of the **degeneracy between flux and cross section effects**.
- **Study energy dependence of neutrino interaction processes**.





On-/Off-Axis Selection Overview

- Signal definition: one negatively charged muon, zero pions, and any number of hadrons detected in the final state. The vertex is reconstructed in the FGD1 or Proton Module Fiducial Volumes (FV).
- Signal samples are categorized by the (sub-)detectors used in the event, and the analysis includes several control samples to constrain background events.
- Events are characterized by muon kinematics
- The extracted cross section is double differential in the muon kinematics.