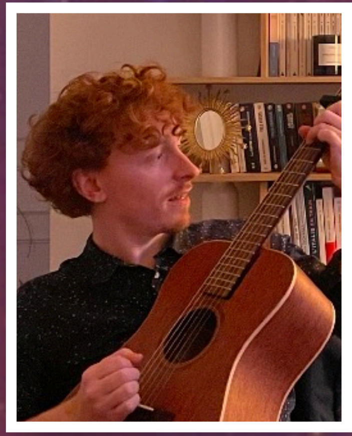
GUNDAM fitter for T2K

Physics is hard, statistical analysis should be easy

Adrien Blanchet
DPNC - (Geneva)

IRN @ IJCLab



The 17th of November - 2022

Mobile Suit Gundam

STEREO oscillation analysis

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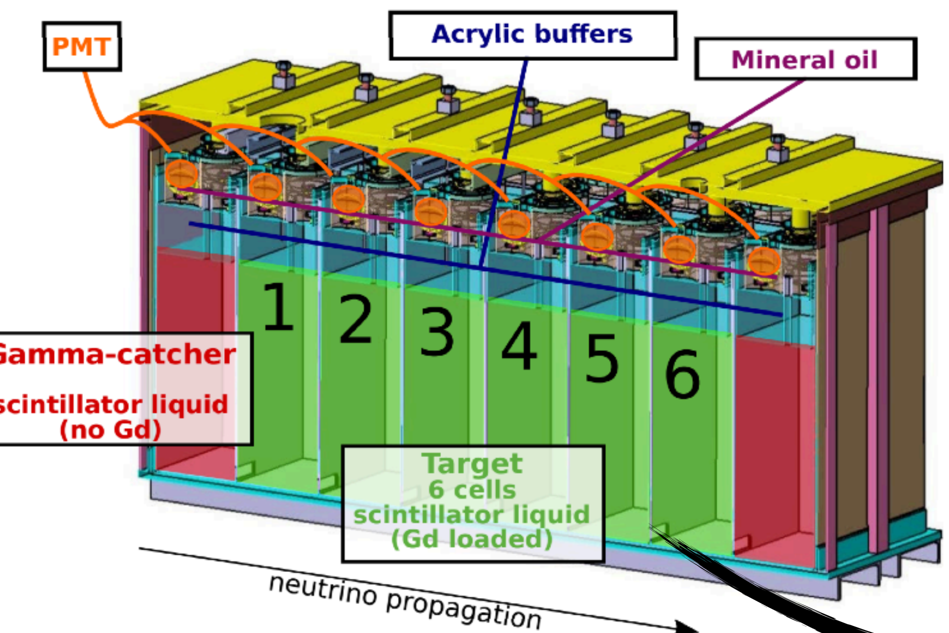
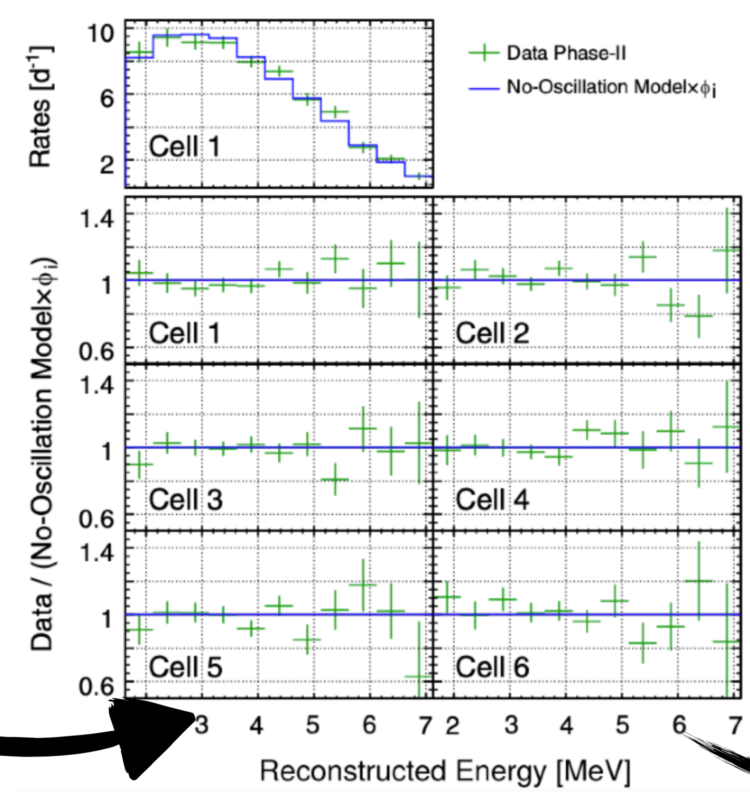
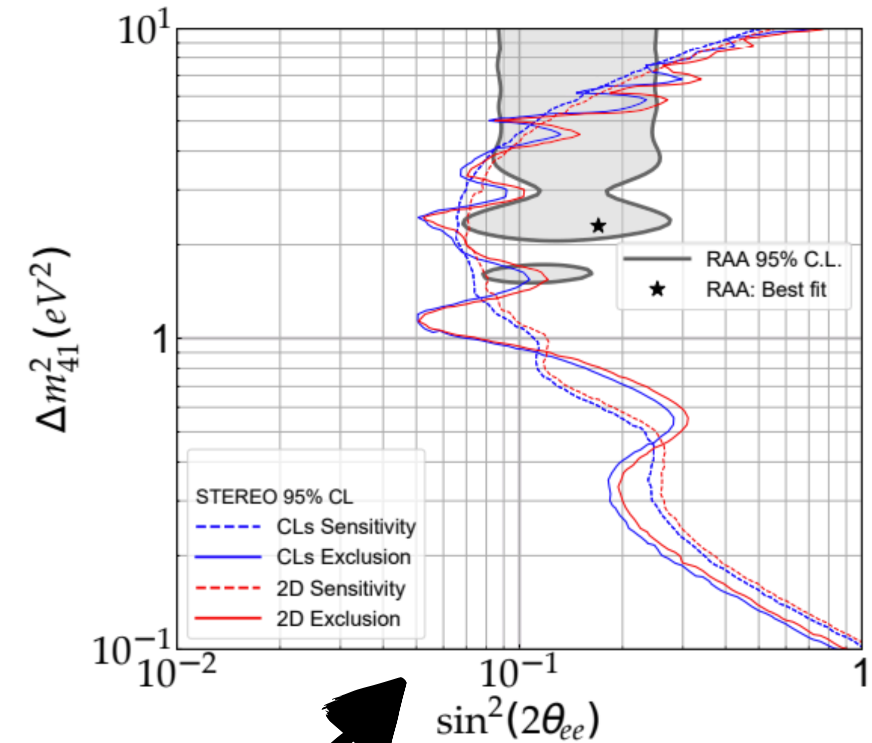
- Look for relative distorsions on the neutrino spectra
- Low neutrino energy: inverse beta decay interactions only (CCQE)



See Rudolph talk!



10.1103/PhysRevD.102.052002



https://arxiv.org/abs/2210.07664

Very few systematics!

- No flux related errors
- No Neutrino-nucleus cross-section systematics
- Only detector uncertainties involved

TABLE II. Overview of relative systematic uncertainties entering the oscillation analysis (Sec. XI). Cell-to-cell correlated normalization parameters are not listed, since the oscillation analysis is insensitive to common shifts among detector cells.

Type	Relative uncertainty	Reference
Normalization (uncorrelated)		
Cell volume	0.83%	Sec. II B
Neutron efficiency correction	0.84%	Sec. VIII
Energy scale (uncorrelated)		
Mn anchor point	0.2%	Sec. VI B
Cell-to-cell deviations	1.0%	Sec. VI F
Energy scale (correlated)		
Time stability	0.3%	Sec. VI D

T2K oscillation analysis

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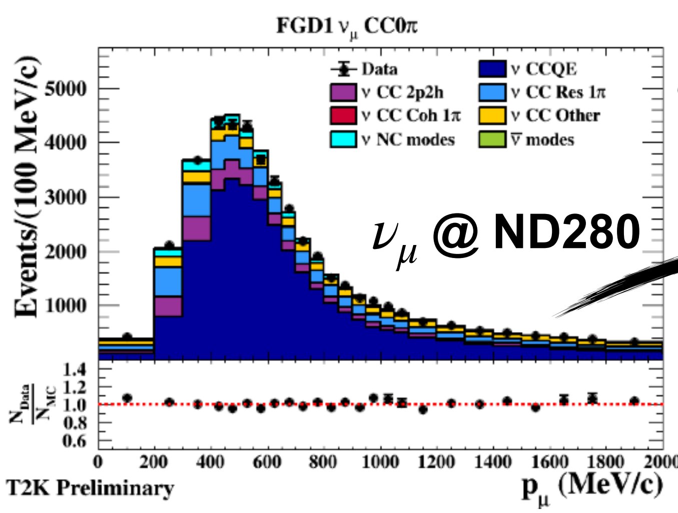
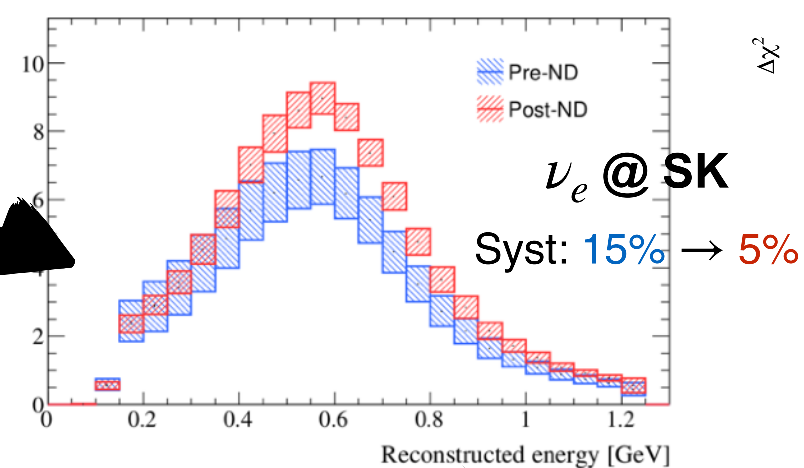
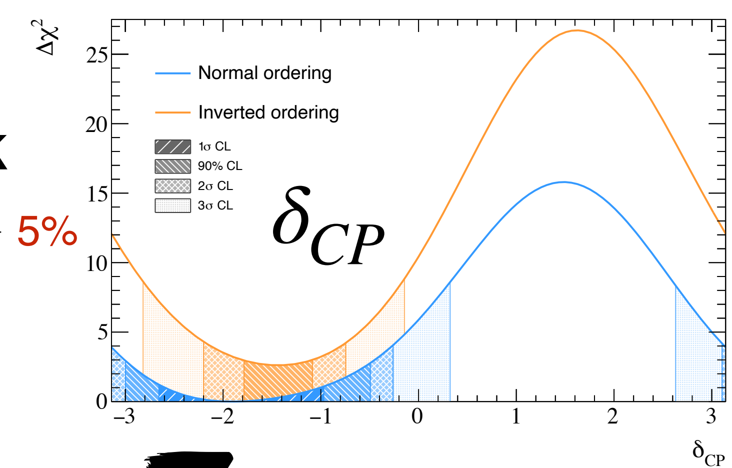
- A total of **~1000 fit parameters** to include in the analysis (flux, cross-section, detector uncertainties)
- **Very fast software tools required** to measure the oscillation parameters

$$\left\{ \nu \text{ Flux models} \right\} \times \left\{ \nu \text{ cross-section models} \right\} \times \left\{ \text{SK detector model} \right\} \times \left\{ \text{oscillation parameters} \right\} = \left\{ \text{Observed event rate} \right\}$$



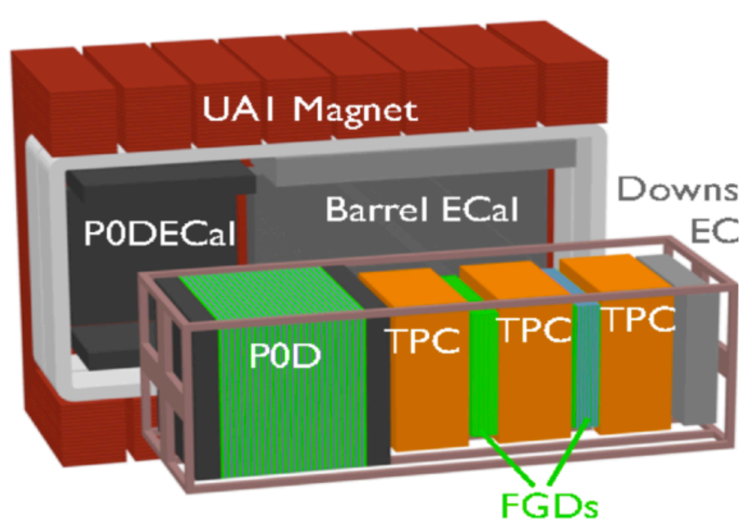
***Constrains and corrects** flux & cross-section systematics*

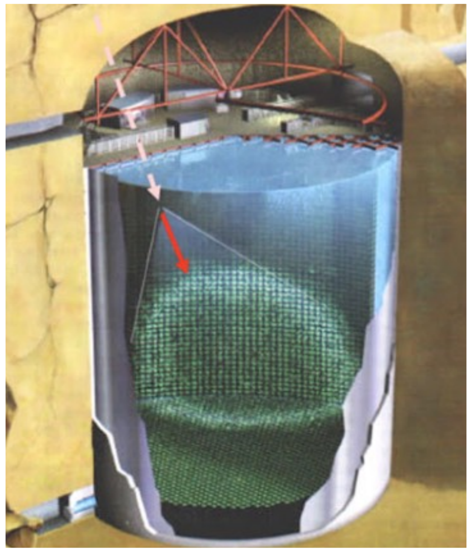




Phys. Rev. D 103, 112008

See Jaafar's talk!





280 m

Beam direction

300 km

Toward Hyper-Kamiokande & DUNE

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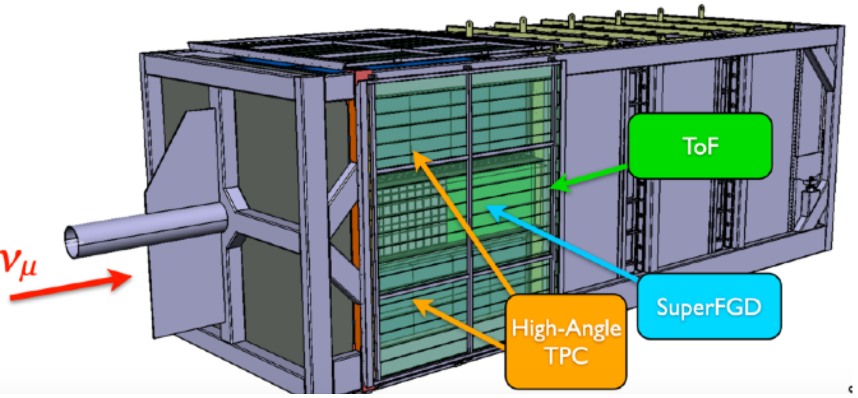
$$N_l(E_\nu) = P(\nu_\mu \to \nu_l)(E_\nu) \times \phi_{\nu_l}(E_\nu) \times \sigma_{\nu_l}(E_\nu) \times \epsilon_l(E_\nu)$$

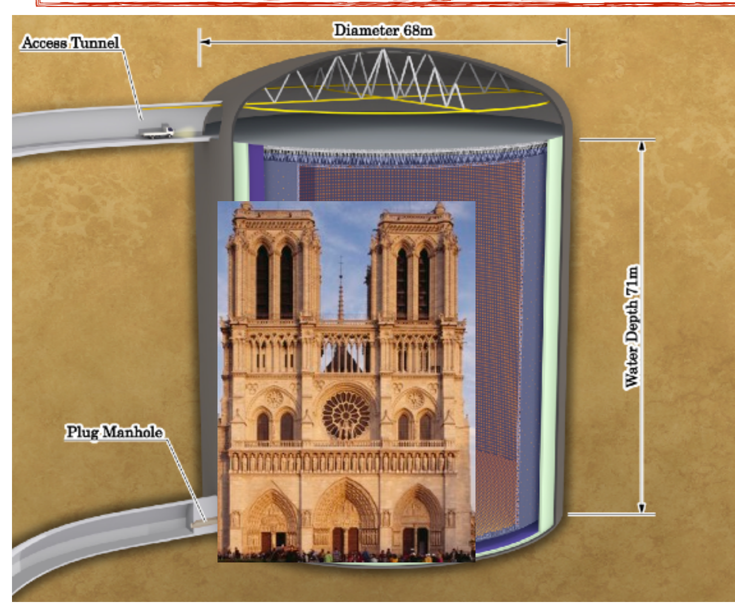
Requested control on systematics ~2 - 3% → new parameters

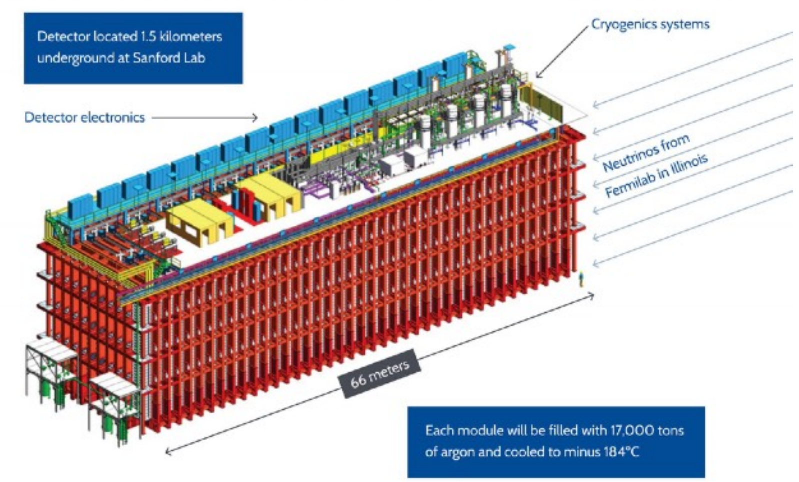
T2K Phase-II
2023 → 2027
$\sim 400\ \nu_e + \bar{\nu}_e$

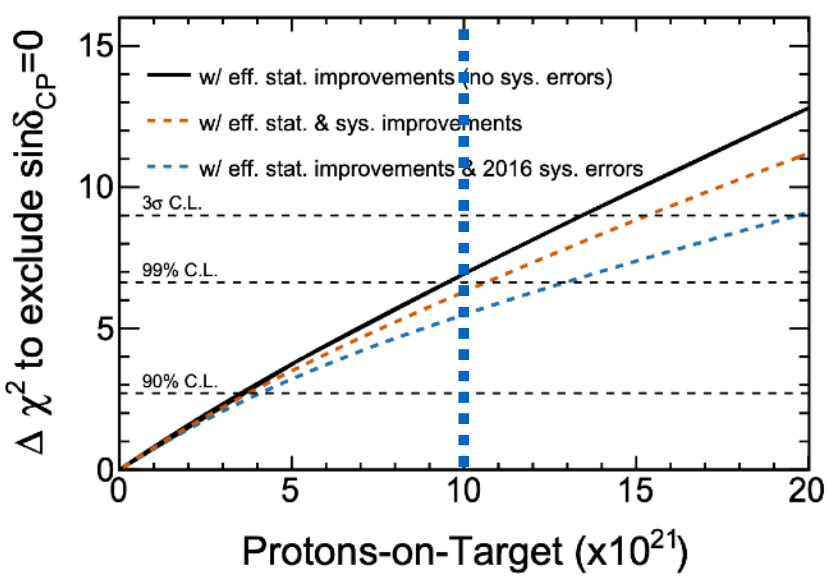
Hyper Kamiokande
2027 → 2037+
$\sim 2000\ \nu_e + \bar{\nu}_e$

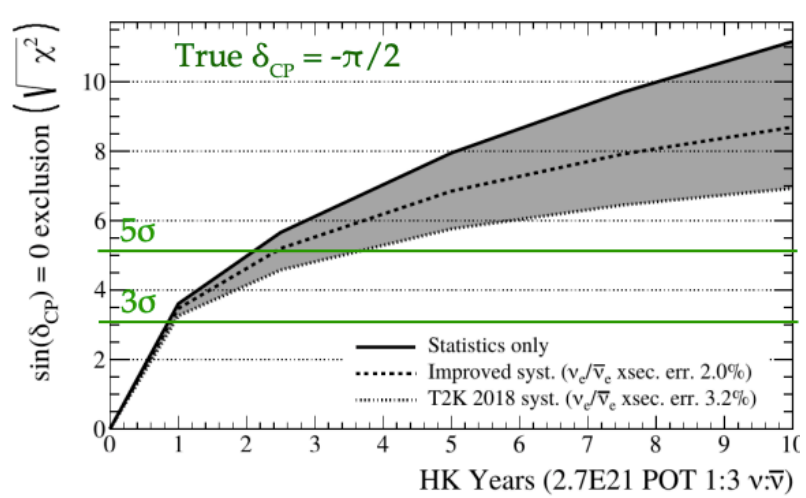
DUNE (staged)
2028 → 20XX
$\sim 1000\ \nu_e + \bar{\nu}_e$ (& ν_τ)

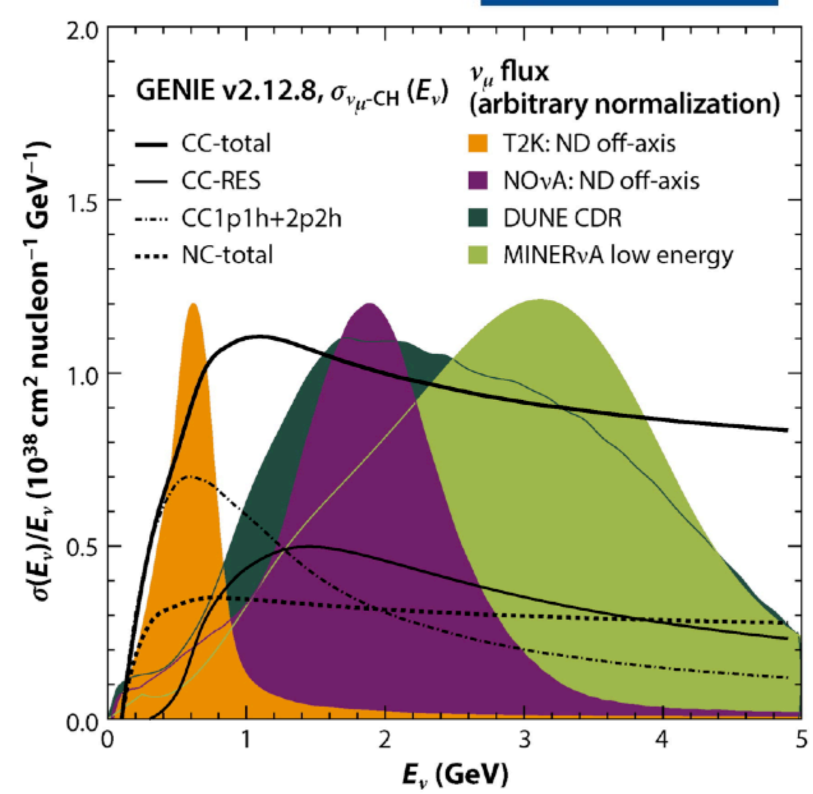












See Benjamin's talk!

Addressing upcoming challenges in T2K

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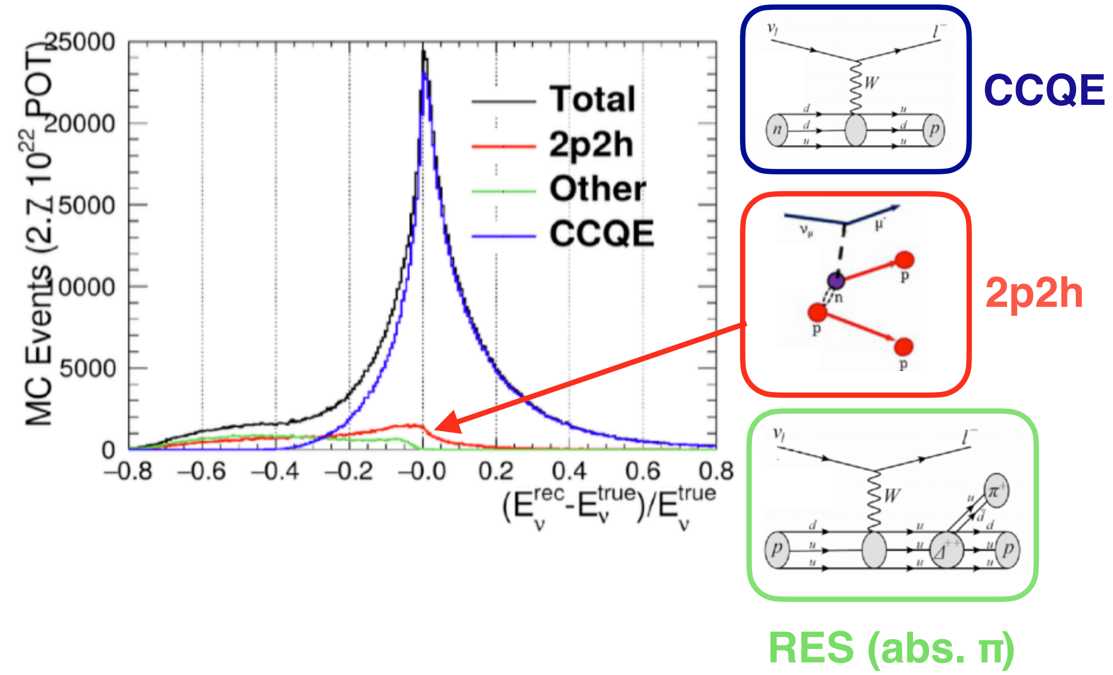
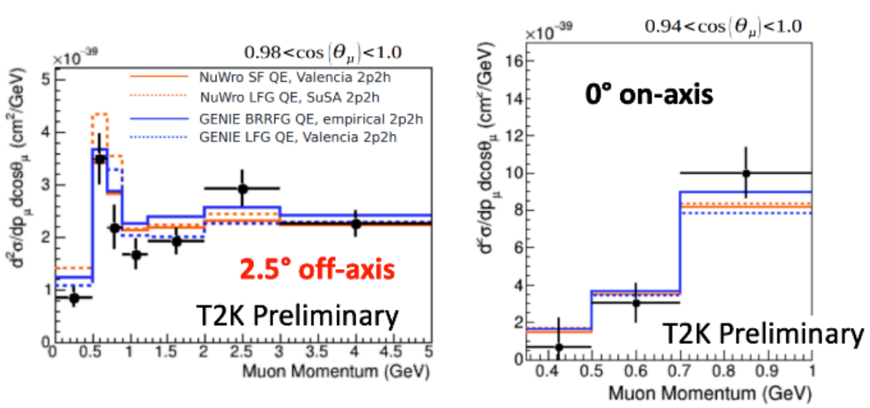
Improving knowledge on ν-nucleus interactions

- Lepton kinematic has different E_ν dependencies with interaction channels
- Need of the relative proportions of these for applying the oscillation probability correctly
- Develop interaction models for a better description of the outgoing particle cinematic & create new systematic response functions



Cross-section measurements

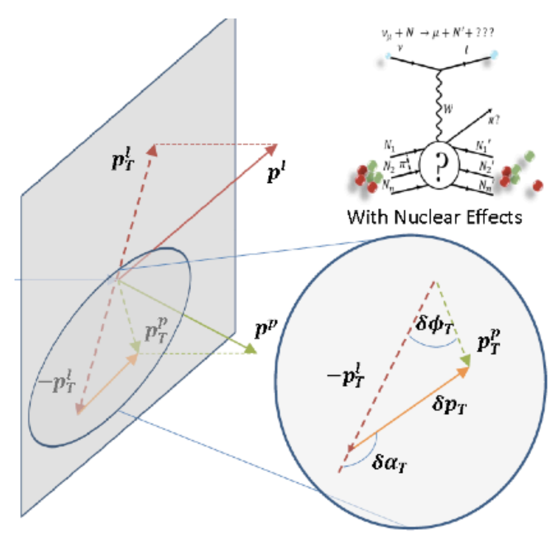


Caspar Schloesser @ NuInt22

Expand the phase-space at ND280

Lepton kinematic → transverse kinematic imbalance

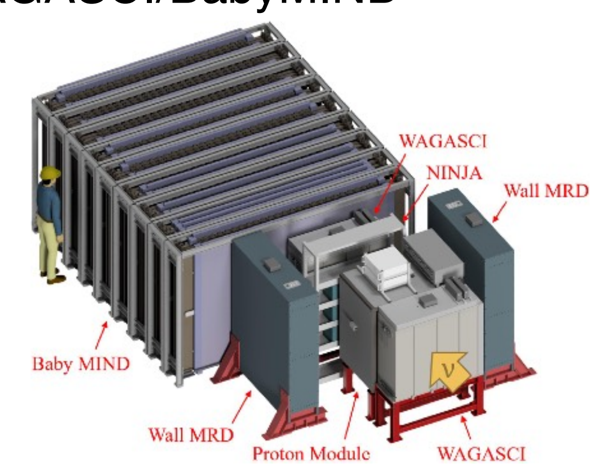
$$(p_\mu, \cos\theta_\mu) \rightarrow (\delta p_T, \delta\alpha_T, p_n \ldots)$$



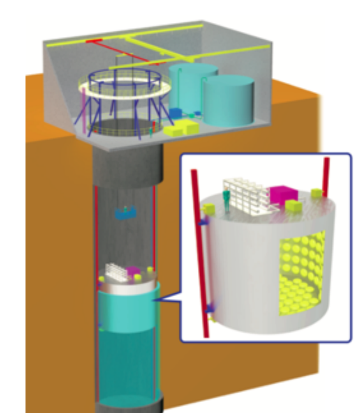
See Marco's talk!

Joint-fits with other NDs

WAGASCI/BabyMIND



ICWD



A common software for statistical analysis?

What is GUNDAM?

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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

develop/adrien ▾ gundamInputOa2020 / inputs / parameters / configParSet.yaml Go to file ···

nadrino renaming option (retro compatible tho) Latest commit 21f114c 6 days ago History

2 contributors

Parameter propagation engine

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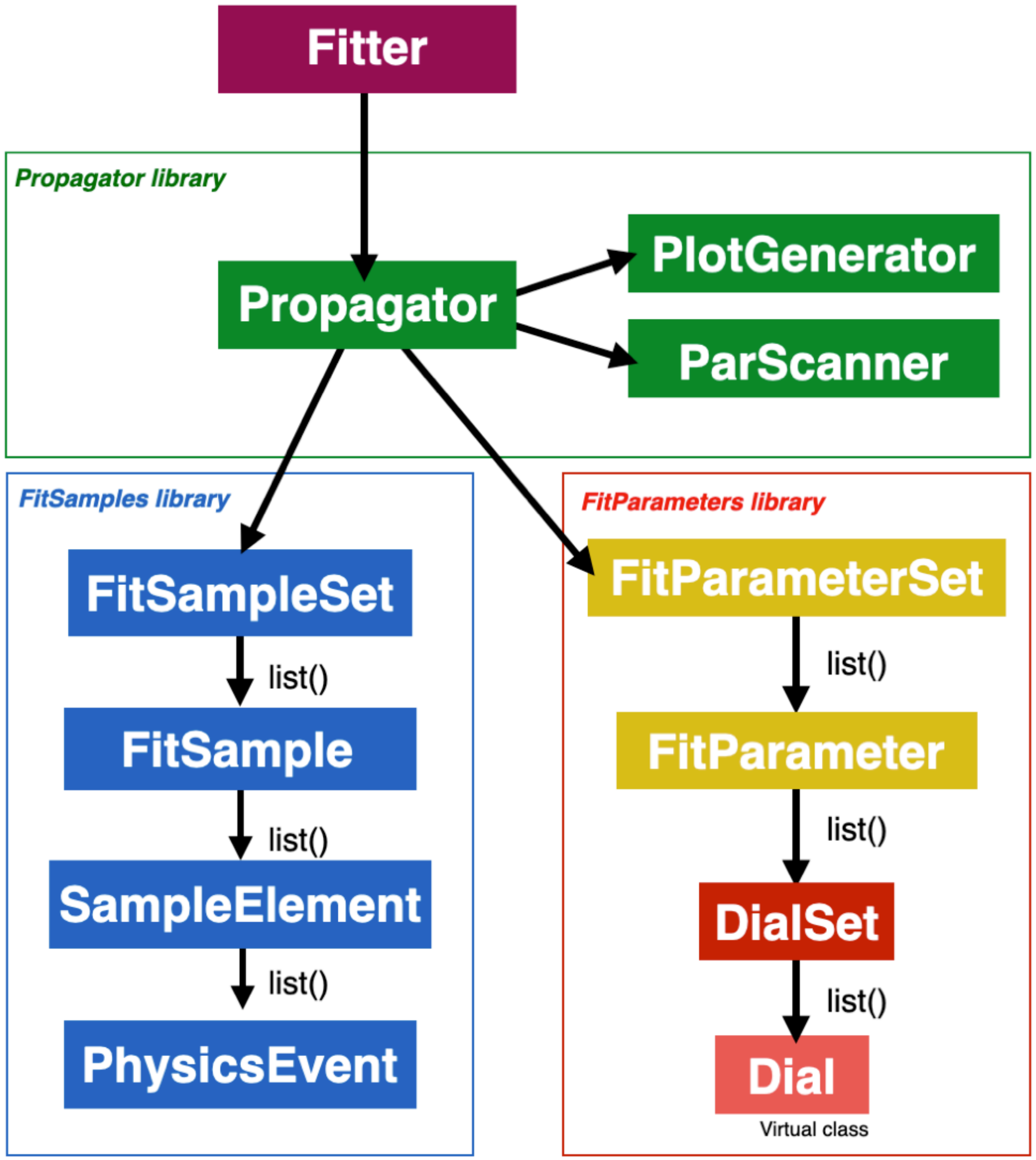

Flexible data handling structure

- Generic sample definition
- Parameter definition with multiple options
  - Covariance matrix
  - Apply conditions
  - Per dataset response function

Config & usage by a single gear: Propagator

- Initialise samples & parameters
- Fast propagation engine (optimised & parallelised)
- Embeds diagnostic tools (figure generators)

Example of configuration: samples

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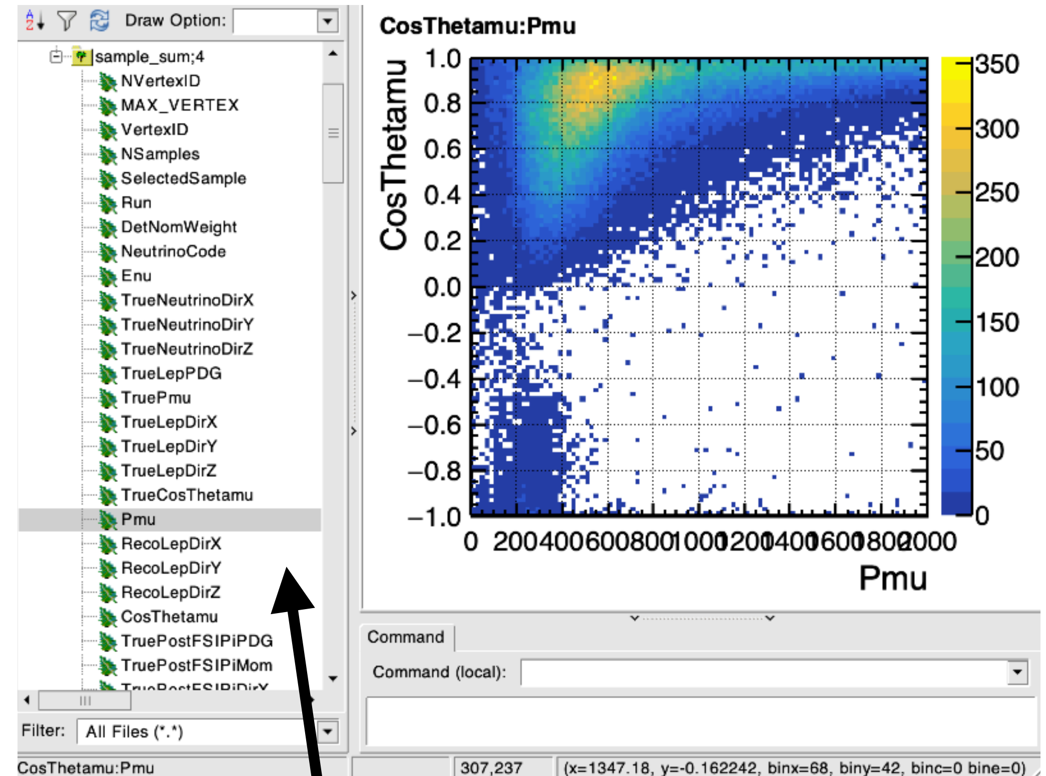
Sample definition using common ROOT tools

- Loads data from TTree
- Define selection cuts & N dimensional binning
- Specify which dataset the sample should be using (joint analysis with multiple detectors)




```yaml
fitSampleList:

  ##########################
  # FHC
  ##########################

  # Samples definition :
  - name: "FHC FGD1 #nu_{#mu} CC 0#pi"
    isEnabled: true
    binning: "./inputs/samples/binnings/FHCNumuCC0Pi.txt"
    selectionCuts: "SelectedSample == 3" # kFGD1NuMuCC0Pi
    dataSets: [ "ND280" ]

  - name: "FHC FGD1 #nu_{#mu} CC 1#pi"
    isEnabled: true
    binning: "./inputs/samples/binnings/FHCNumuCC1Pi.txt"
    selectionCuts: "SelectedSample == 4" # kFGD1NuMuCC1Pi
    dataSets: [ "ND280" ]
```

```
variables: CosThetamu CosThetamu Pmu Pmu
-1 0.5 0 200
-1 0.5 200 300
-1 0.5 300 400
-1 0.5 400 450
-1 0.5 450 500
-1 0.5 500 550
-1 0.5 550 600
-1 0.5 600 650
-1 0.5 650 700
-1 0.5 700 750
-1 0.5 750 800
-1 0.5 800 850
-1 0.5 850 900
-1 0.5 900 950
-1 0.5 950 1000
-1 0.5 1000 1050
-1 0.5 1050 1100
-1 0.5 1100 1200
```

Example of configuration: parameters

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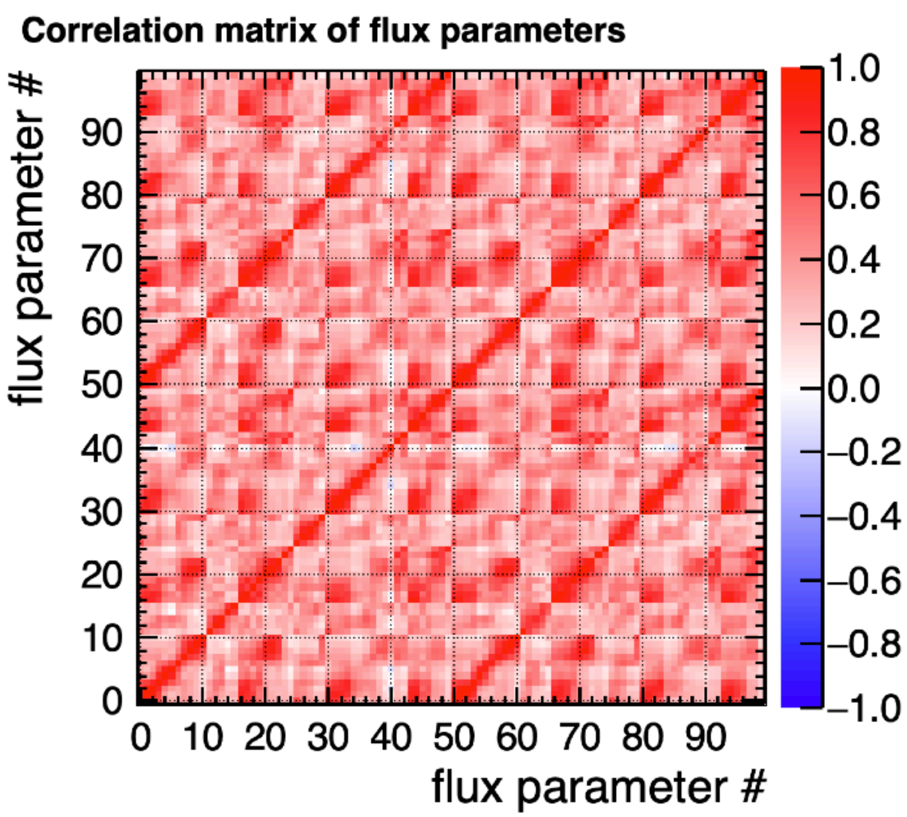
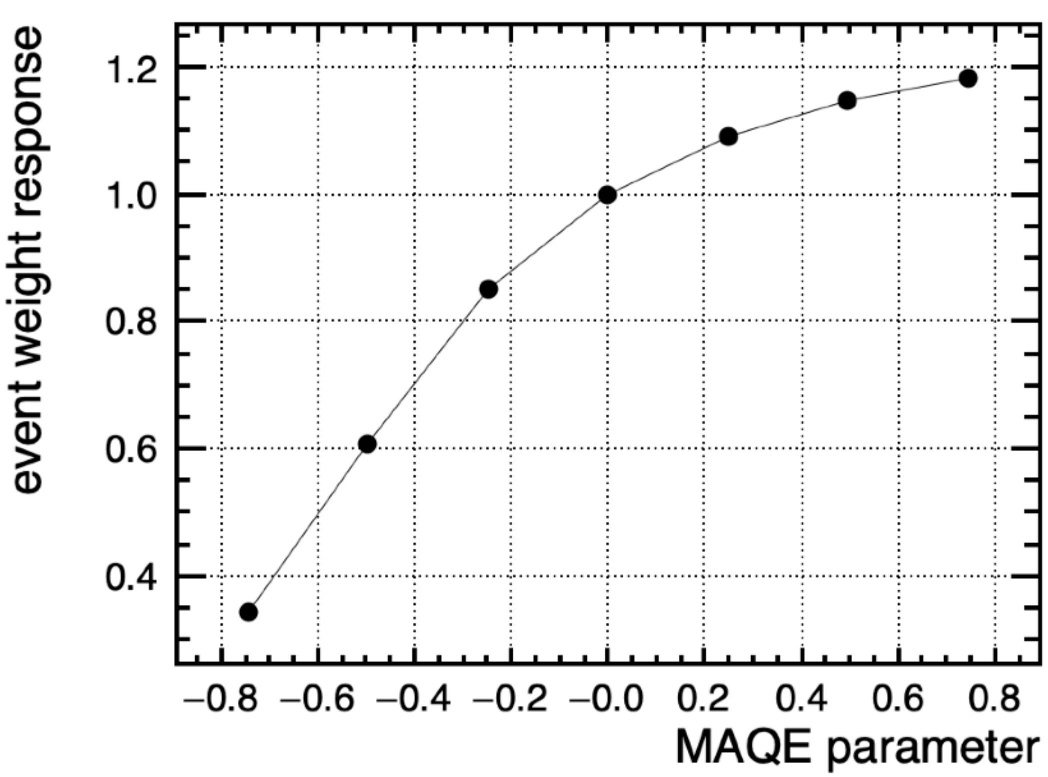
Define fit parameters & how they should apply

- Parameter prior values / limits / names
- Add prior covariance matrices
- Option for Eigen decomposition
- Define response functions (Dials) for each dataset
    - Support for multiple dial types: Normalisation / Graph / Splines
    - Binned or event-by-event dials





Auto-generated outputs

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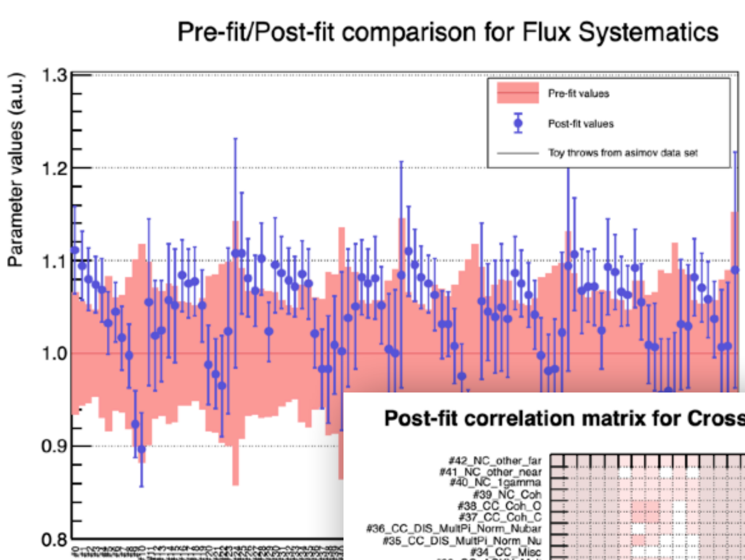
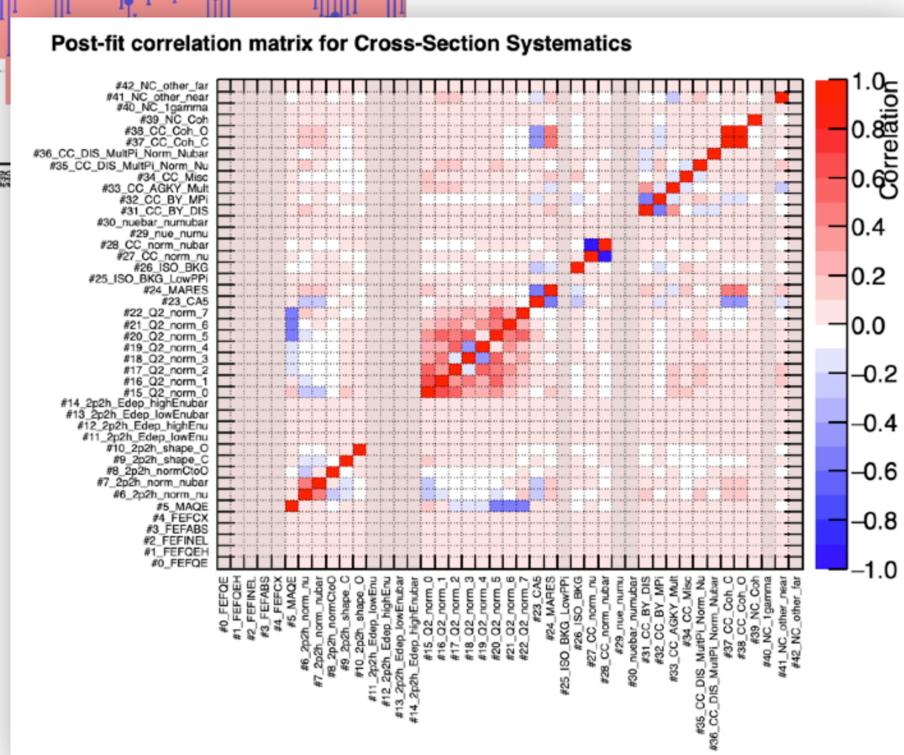
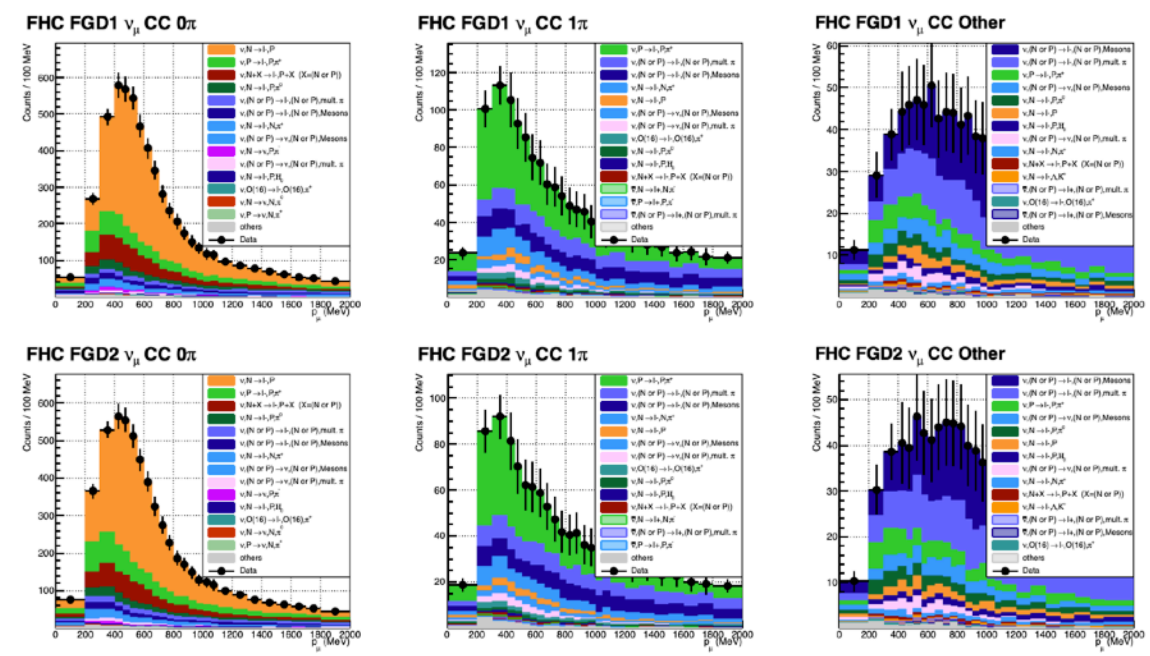
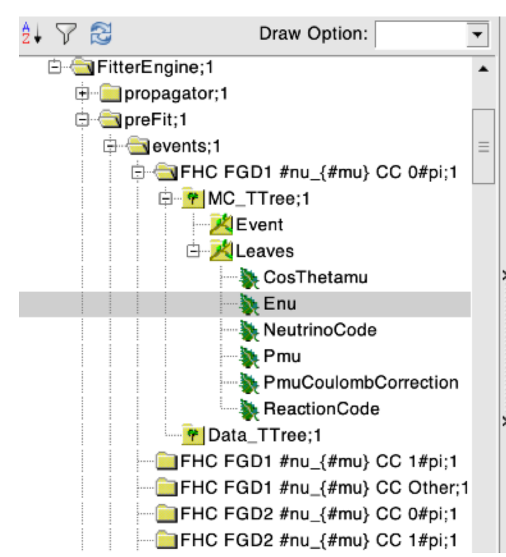
Configurable figures and data generator in the output ROOT file

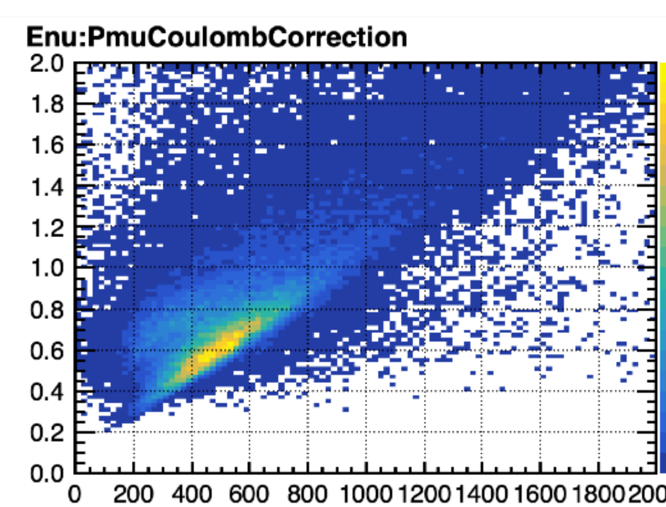
- Debug info (command line, full JSON configuration, GUNDAM version…)
- Fit histograms / projection on a given variable / breakdowns
- Likelihood parameter scans
- Event rate monitoring wrt parameter variations
- Loaded sample events data in TTree
- Post-fit values, error, covariance, hessian decomposition











More features

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Flexible data handling structure

- Toy data fits
- Eigen decomposition
- Principle component analysis for highly correlated parameters
- Alternative fitter algorithms (Migrad, Simplex, Combined…)
- User compiled C++ code (plugins)
  - Custom likelihood functions definition
  - Custom variable definitions
  - Custom dials functions (WIP)

Documentation available

21 lines (15 sloc) | 1.59 KB   Raw   Blame

Propagator

< back to parent (FitterEngine)

Description

Config options

Option	Type	Description	Default
fitSampleSetConfig	json	FitSampleSet config	
parameterSetListConfig	json	ParameterSetList config	
dataSetList	json	DatasetManager config	
plotGeneratorConfig	json	PlotGenerator config	
showEventBreakdown	bool	Print sample total weight	true
enableStatThrowInToys	bool	Throw statistical error with a poisson distribution	true
enableEventMcThrow	bool	Each MC event get reweighted with Poisson(1)	true
throwAsimovFitParameters	bool	Throw parameters of MC before fit (used to test fitter convergence)	false

Optimisation: parallelising tasks

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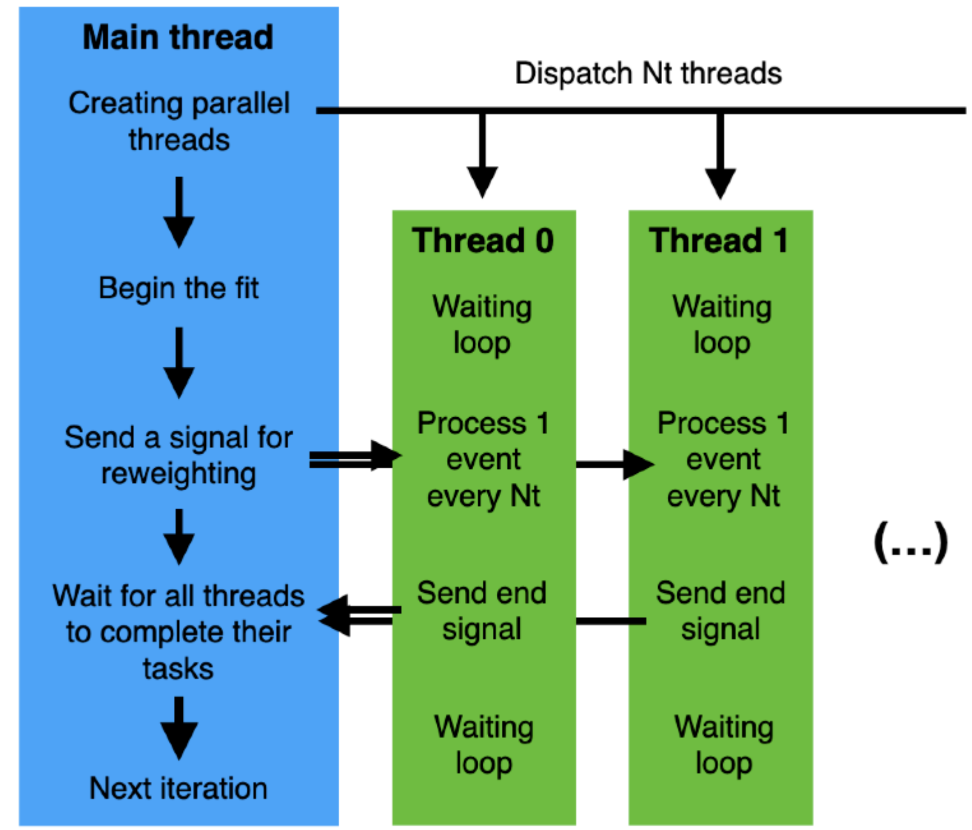

Parameter propagation is fully parallelised using CPU thread workers

- 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

Validated with T2K latest oscillation analysis

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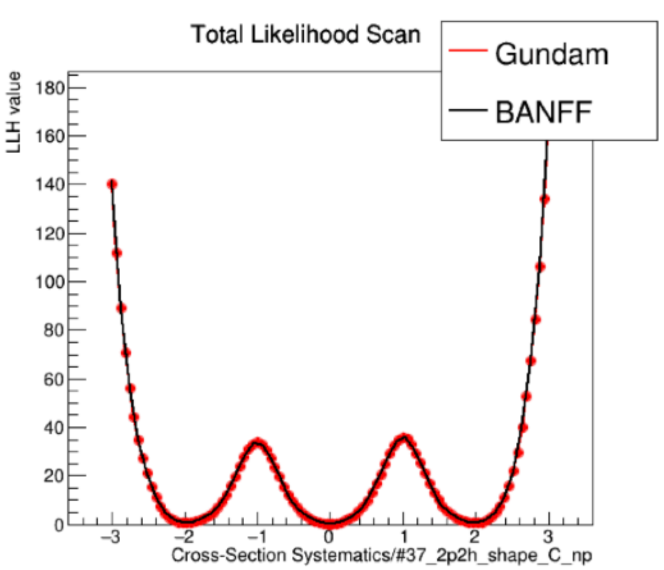
Complete validation requested for GUNDAM to takeover

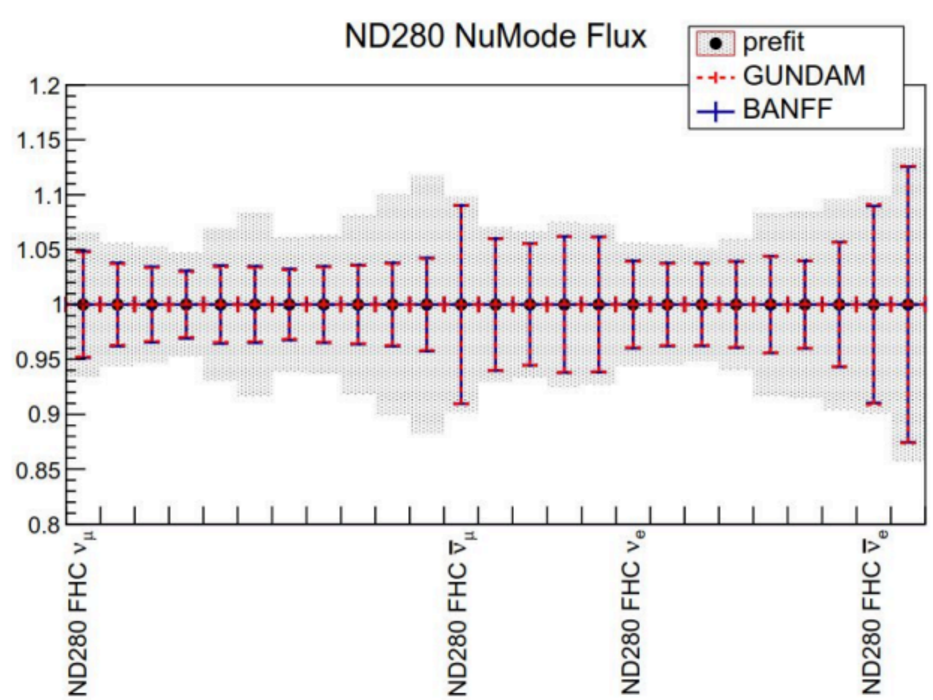
- Compare with latest OA results performed with the original tool (BANFF)
- Numerous checks performed
  - Checked event rates wrt every parameters (± 1, $\pm 3\sigma$)
  - Checked likelihood scans
  - Checked post-fit errors and best-fit values (Asimov + Data fits)
  - Checked the generated contours on oscillation parameters
  - Checking toy fits χ^2 distributions

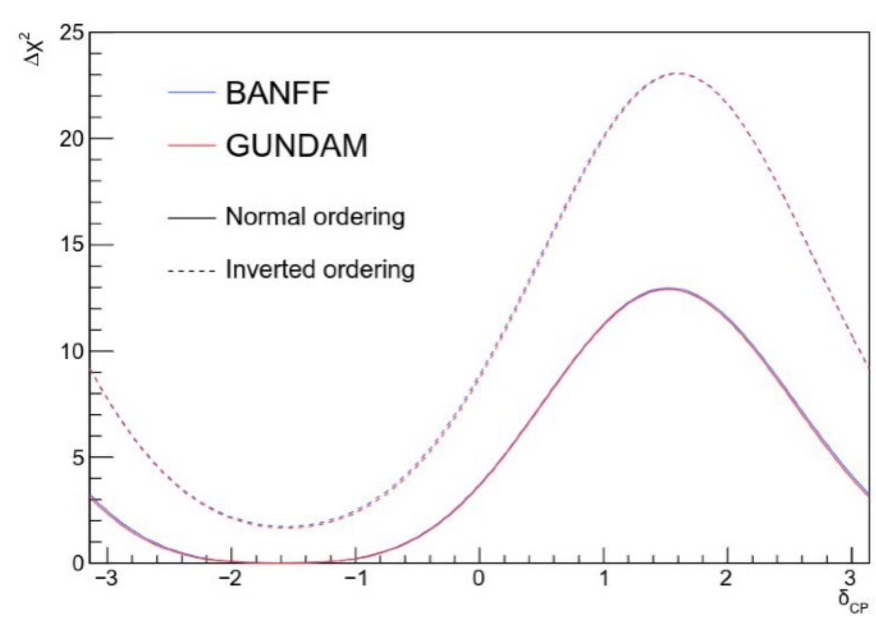
Dial	Sample	(G-B)/G at -1σ
ND280 FHC ν_μ [0, 0.4 GeV] = 1 ± 0.0658425	FHC FGD1 ν_μ CC0π	-8.76256e-09
	FHC FGD1 ν_μ CC1π	1.45984e-07
	FHC FGD1 ν_μ CCOth	-6.59672e-15
	FHC FGD2 ν_μ CC0π	7.2623e-08
	FHC FGD2 ν_μ CC1π	-9.56866e-08
	FHC FGD2 ν_μ CCOth	2.8355e-07
	RHC FGD1 $\bar{\nu}_\mu$ CC0π	8.63167e-15
	RHC FGD1 $\bar{\nu}_\mu$ CC1π	1.63738e-15
	RHC FGD1 $\bar{\nu}_\mu$ CCOth	3.71067e-15
	RHC FGD2 $\bar{\nu}_\mu$ CC0π	-1.29254e-15
	RHC FGD2 $\bar{\nu}_\mu$ CC1π	-1.09194e-15
	RHC FGD2 $\bar{\nu}_\mu$ CCOth	-5.79771e-16
	RHC FGD1 ν_μ (bkg) CC0π	8.83851e-15
	RHC FGD1 ν_μ (bkg) CC1π	-1.56943e-15
	RHC FGD1 ν_μ (bkg) CCOth	-2.9663e-15
	RHC FGD2 ν_μ (bkg) CC0π	1.53978e-14
	RHC FGD2 ν_μ (bkg) CC1π	8.55123e-16
	RHC FGD2 ν_μ (bkg) CCOth	-2.84107e-15

Performance comparison

- **BANFF takes ~6 days → less than 0.5 day with GUNDAM** in the same conditions!
- Up to 1.5 hour using PCA (less fit parameters)







Validated with T2K latest oscillation analysis

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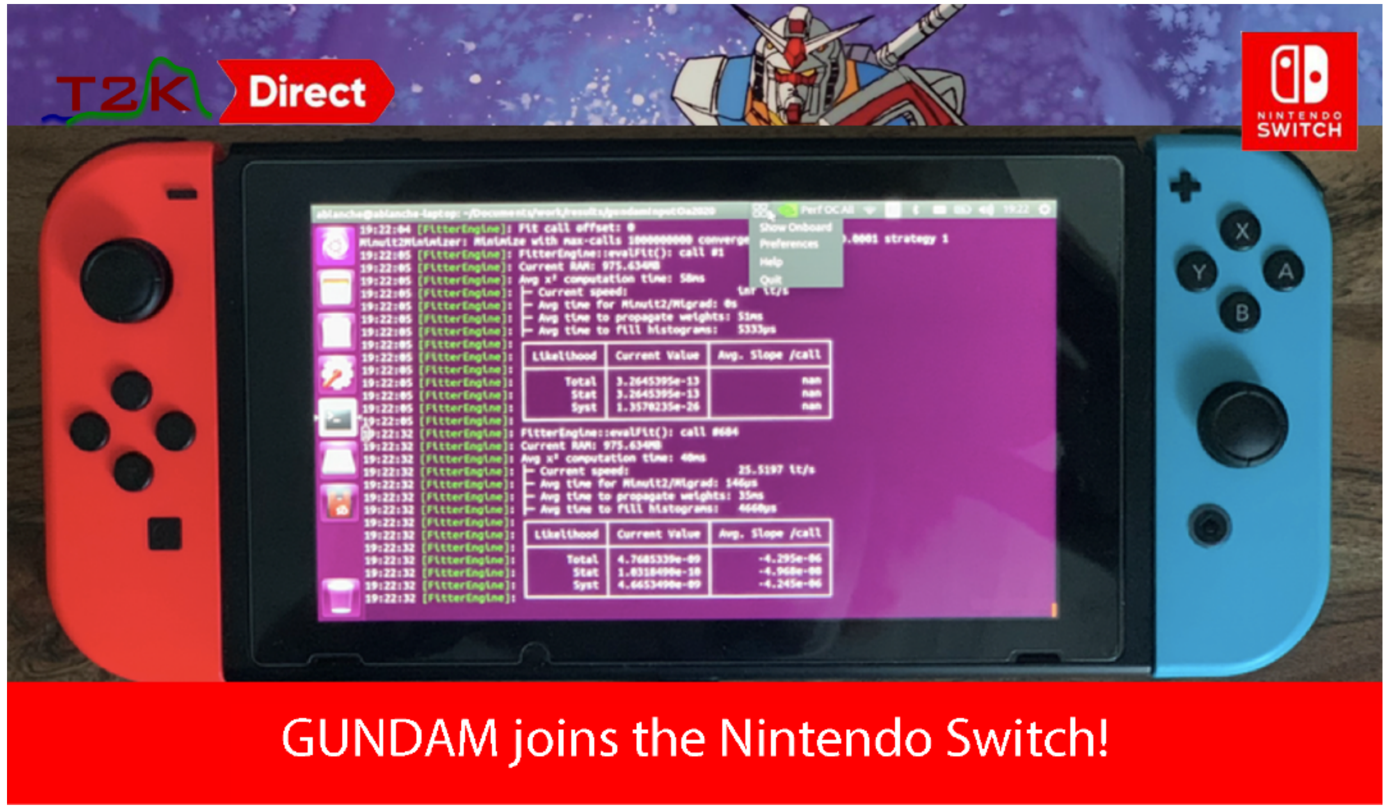
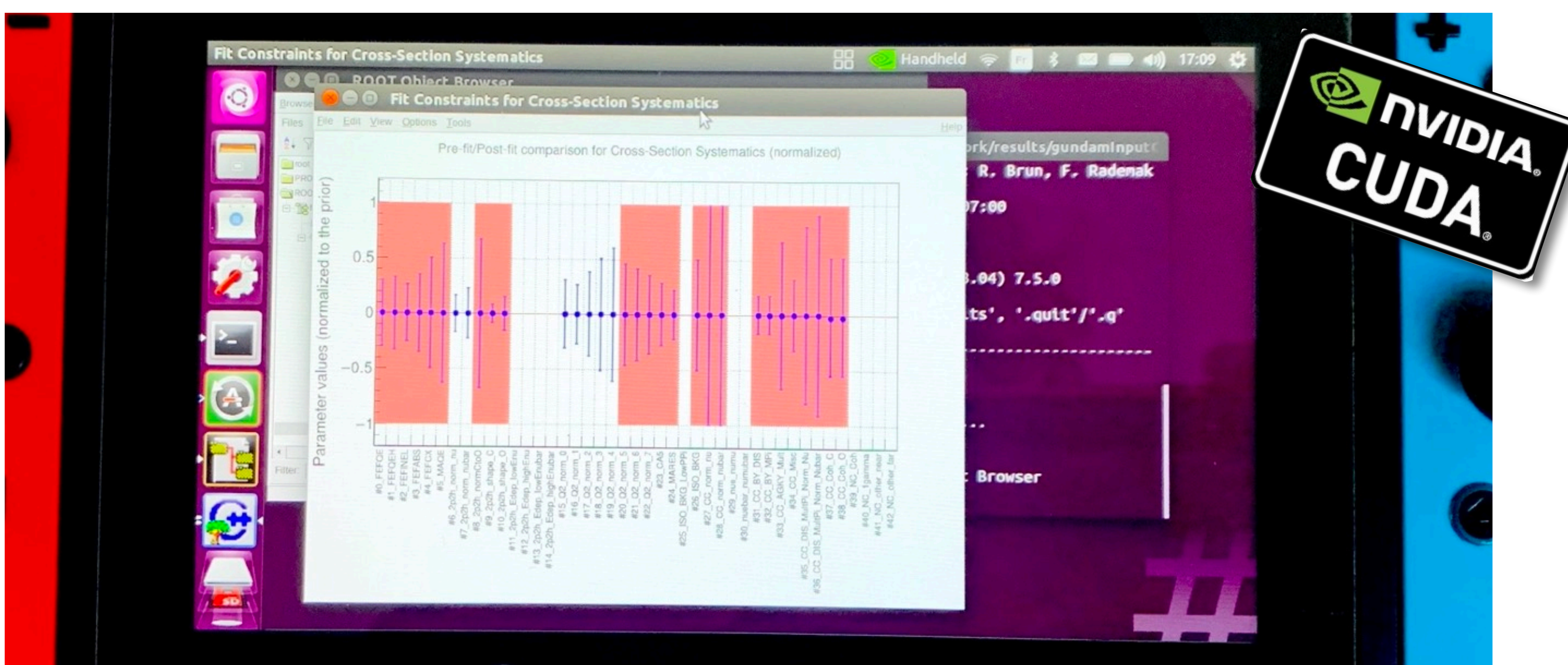


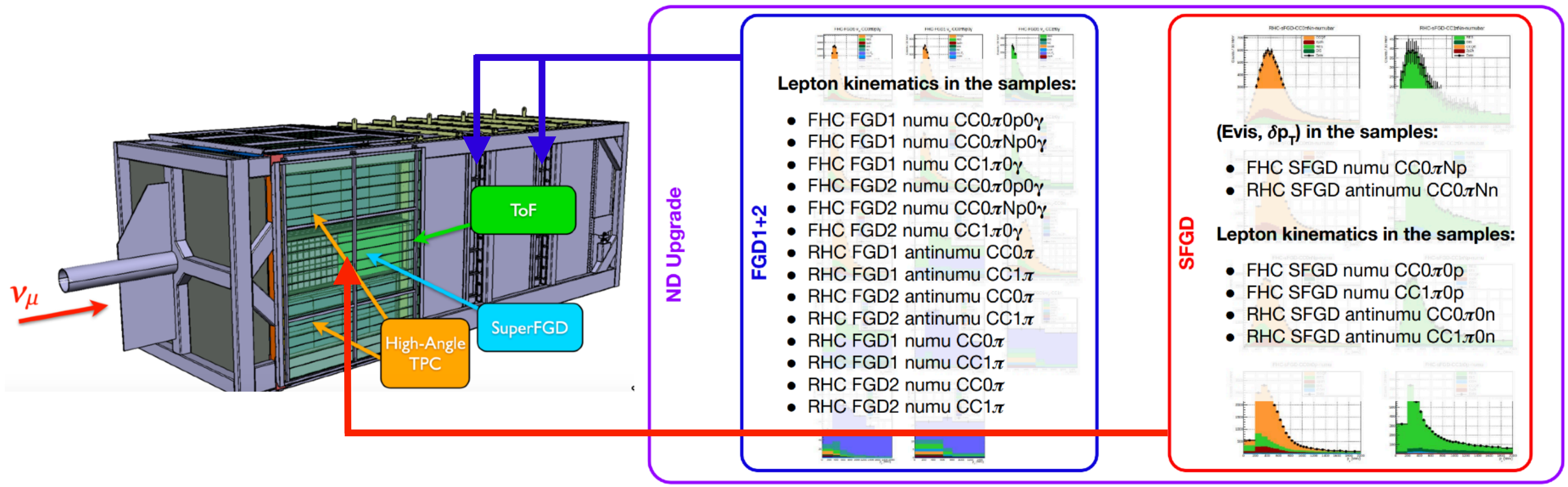


Upgrade Physics with GUNDAM

GUNDAM is ready for the next T2K oscillation analysis!

- GUNDAM has been granted to be the new official tool for next oscillation analysis
- Currently running side to side with the historical frameworks

- Full sensitivity studies for the phase-II of data taking have started:
  - *How should we distribute neutrino vs antineutrino runs?*
  - *How to parametrise new systematics?*
  - *What's the best fitting phase-space to constrain our models?*



Beyond the T2K oscillation analysis

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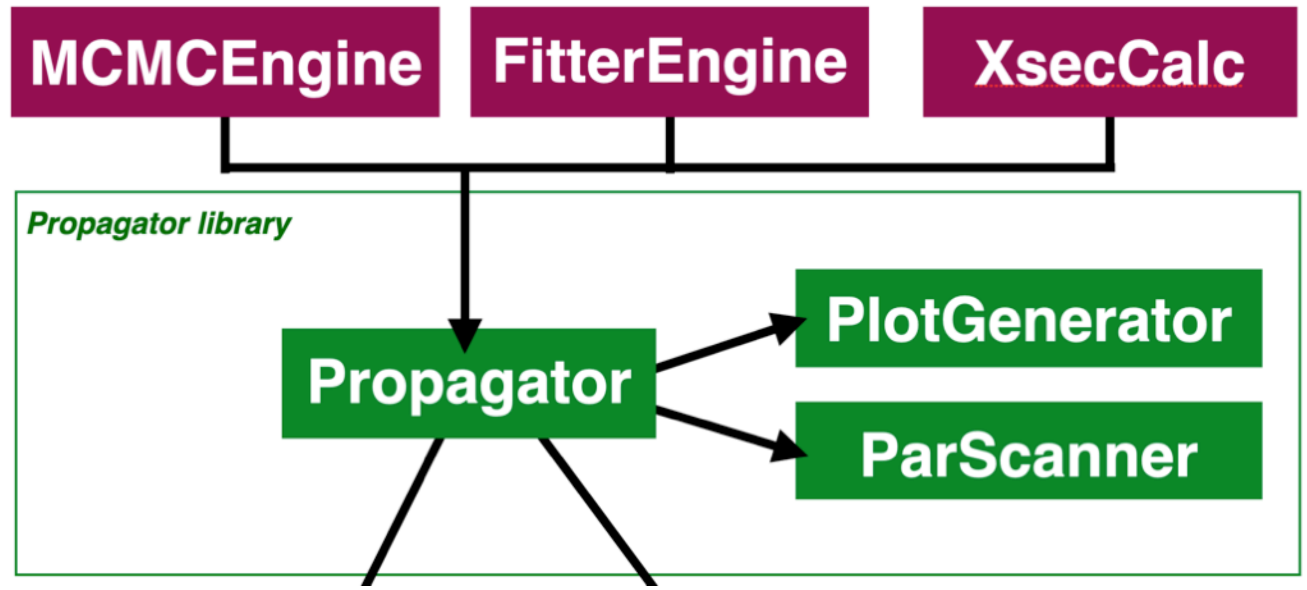

Alternative engines can benefit from the propagator library

- Adding new algorithm that needs to propagate parameters on sample
  - Implementation of Metropolis Hastings MCMC (as done in the alternative T2K OA)
  - Cross-section extraction tool → bringing another working group of T2K in GUNDAM

$$\frac{d^2\sigma}{dp_\mu^i d\cos\theta_\mu^i} = \frac{N_i}{\epsilon_i} \times \frac{1}{T\phi} \times \frac{1}{\Delta p_\mu^i \Delta\cos\theta_\mu^i}$$

True number of signal events

Number of targets / Integrated flux

Bin area

- Space for new extension (Hamiltonian MCMC, response function generator, marginalising tool…)

Beyond the T2K oscillation analysis

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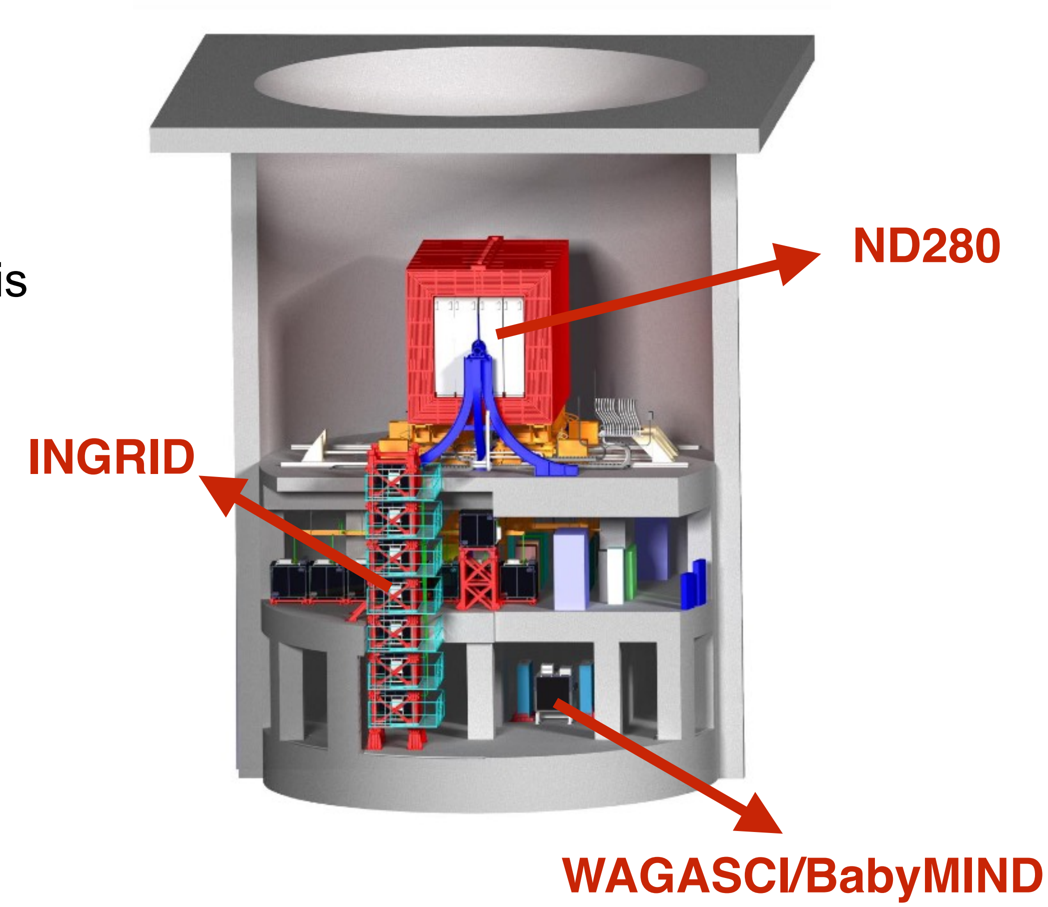
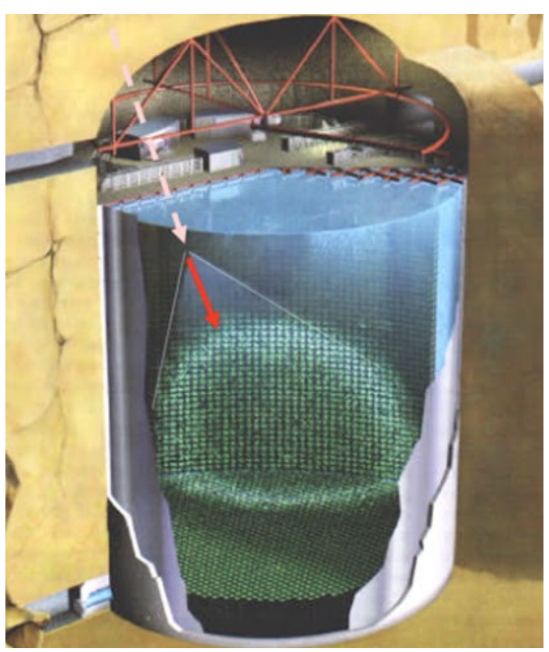
Joint fit using all near detectors of T2K

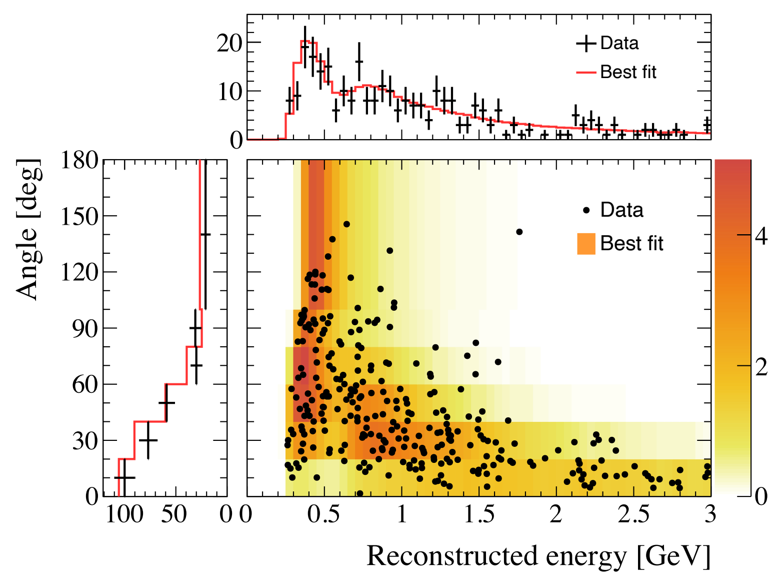
- Along with the upgraded ND280 samples:
  - INGRID: on and off-axis measurement
  - WAGASCI/BabyMIND: water & carbon targets @ 1.5-degree off-axis



…and the far detector?

- Including Super-Kamiokande samples as well
- Fully exploits correlations between the systematic uncertainties
- Propagate oscillation parameters
- Need to implement a Feldman Cousin tool





Use GUNDAM for other experiments?

- As an open source / LGPL software other experiments

Summary

~~Physics is hard, statistical analysis should be easy~~

Physics is fun, statistical analysis should be as well !

GUNDAM as a true next generation fitting tool

- A multipurpose fitter framework to host various T2K analysis
- Using a fast, robust and flexible parameter propagation engine
- Numerous diagnostic and drawing tools
- **Ready to face larger statistics (samples) and nuisance parameters**

GUNDAM for T2K

- Fully validated with the latest oscillation results
- Currently working side to side with the current ongoing analysis
- Ready for phase-II runs (2024+) and next LBL experiments
- Entering cross-section working group

Extending GUNDAM

- Alternative fitter engines
- Joint fits with other near detectors
- Add oscillation parameter & Feldman Cousins tools