High dimensional fitting tools for neutrino oscillation and cross-section analyses

Kamil Skwarczyński

Exploring the Dark Side of the Universe Tools 2024

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Neutrino Measurements

$$N(\vec{x}) = \Phi(E_\nu^{true}) \cdot \epsilon(\vec{x}) \cdot \sigma(E_\nu^{true}, \vec{x}) \cdot P_{osc}(E_\nu^{true})$$

Number of params = ~10-200 ~10-8000 ~10-200 <= 3

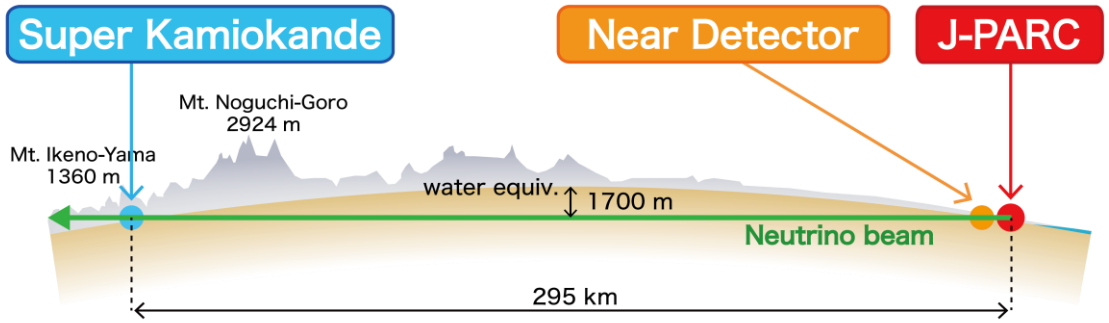
A number of expected events in the far detector of neutrino oscillation measurements like **T2K** or **NOvA** is a combination of:

Flux

Detector Effects

Cross-section

Oscillation



Measurements in neutrino experiment can be divided into:

Cross-section – helpful for better understanding neutrino interactions and valuable input to theorist groups and generator development.

Oscillation - answer the big question of why there is more matter than antimatter, BSM physics etc.

Bright Future !?

Current experiments like **T2K** or **NOvA** are dominated by statistical errors.

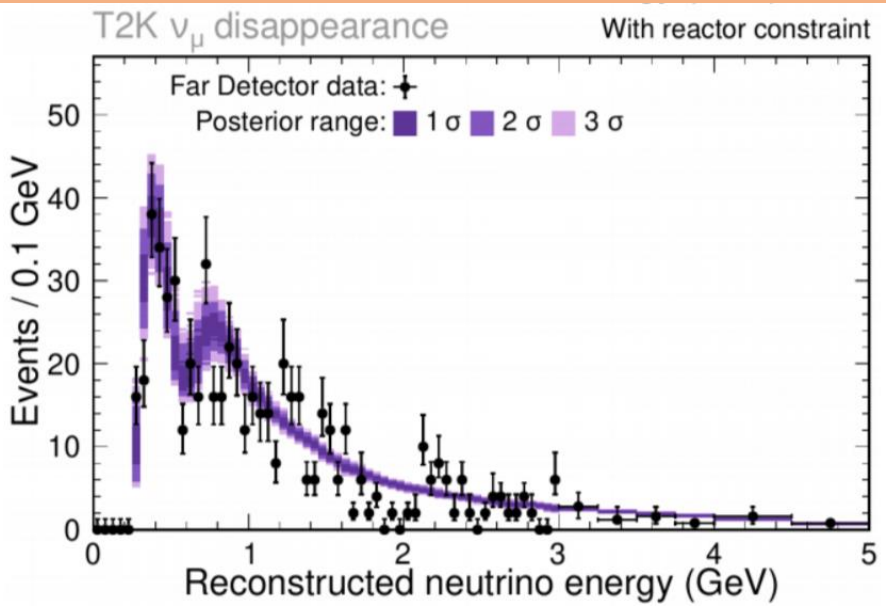
DUNE and **HK** are upcoming neutrino experiments which will have much higher statistics.

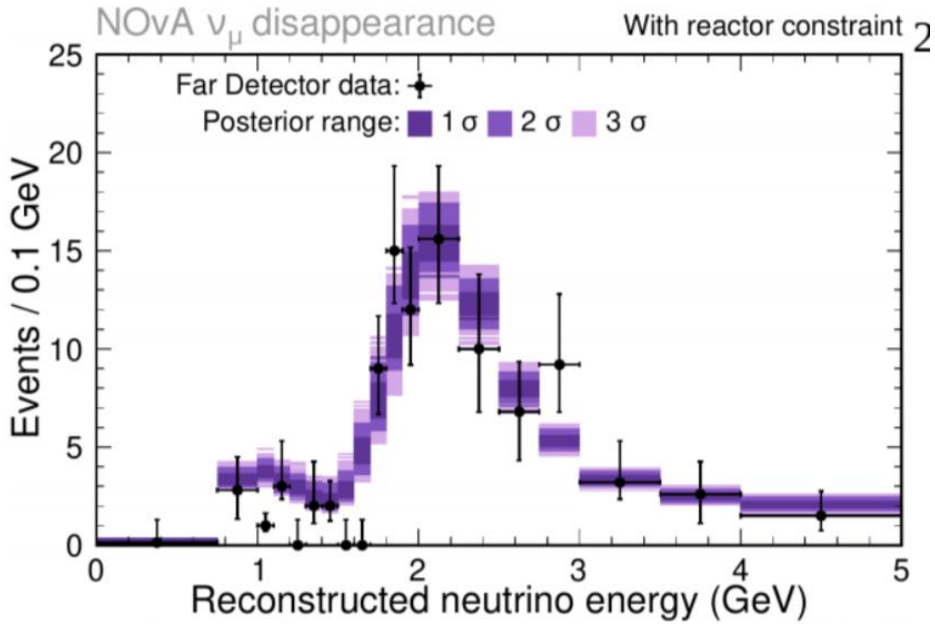
Need more robust systematic models **increasing dimensionality** affecting fitter performance.

Cross-section measurements with higher number of fitting dimensions Using multiple subdetectors (different targets) increasing complexity.

T2K+NOvA and **T2K+SK** analyses have recently had to unify different fitting frameworks. Using common tools for the future will hopefully avoid this unification work

For more see next talk by Clarence

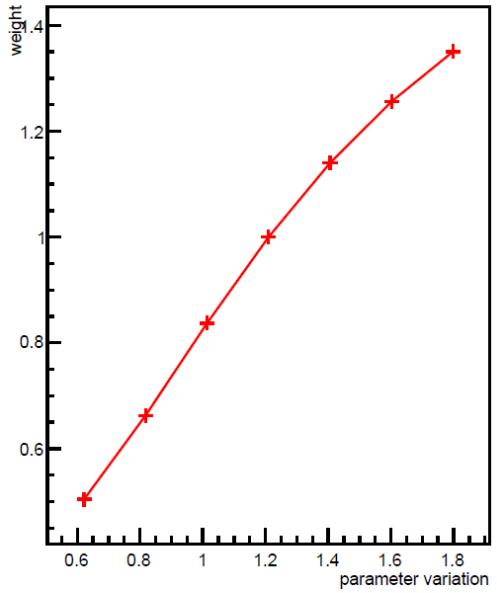




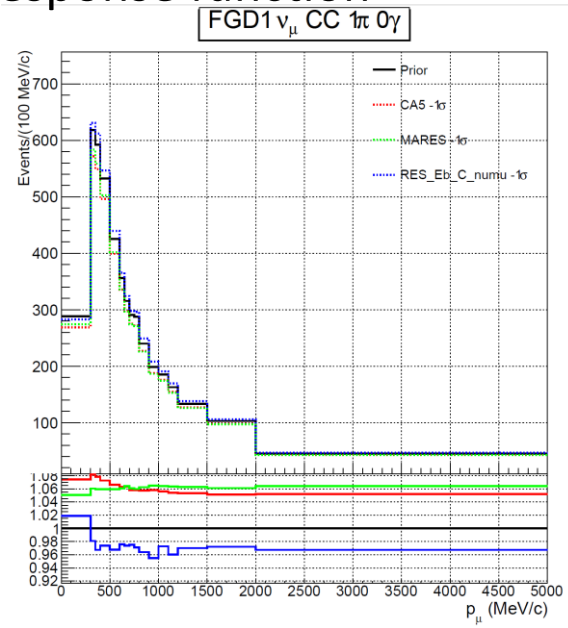
Problems with complex models

Use event-by-event response functions to describe systematic uncertainty.

1D response function



Modification of MC using response function



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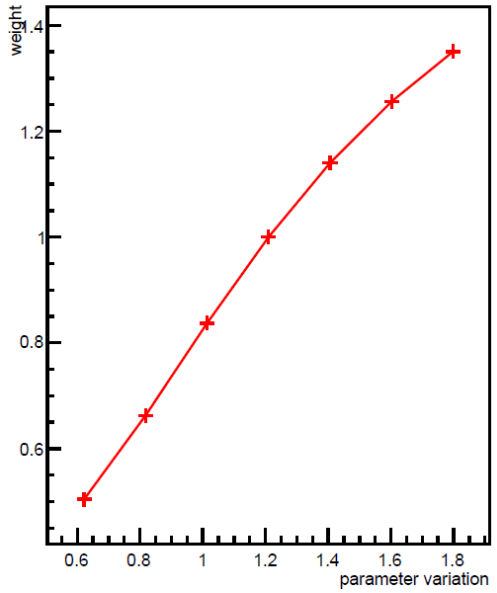
Use event-by-event response functions to describe systematic uncertainty.

Response functions helps modify MC during fit.
Number of parameters with response functions

- T2K 2020 analysis: 18
- T2K 2022 analysis: 48
- T2K 2024 analysis: 160

Even 30M objects -> impact RAM, speed performance etc.

1D response function



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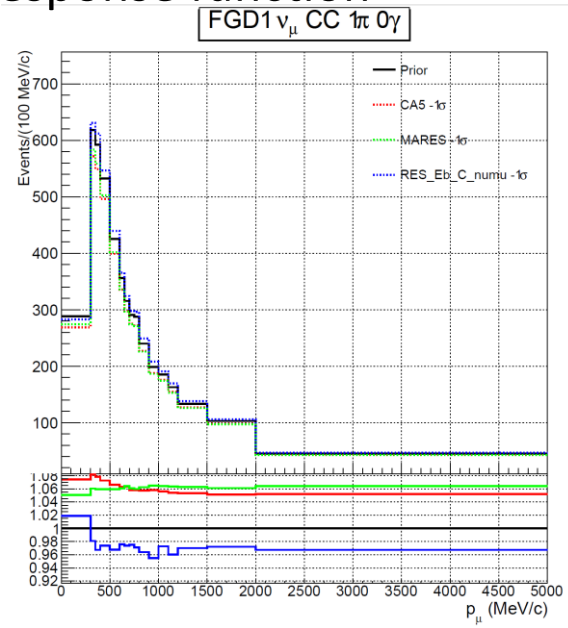

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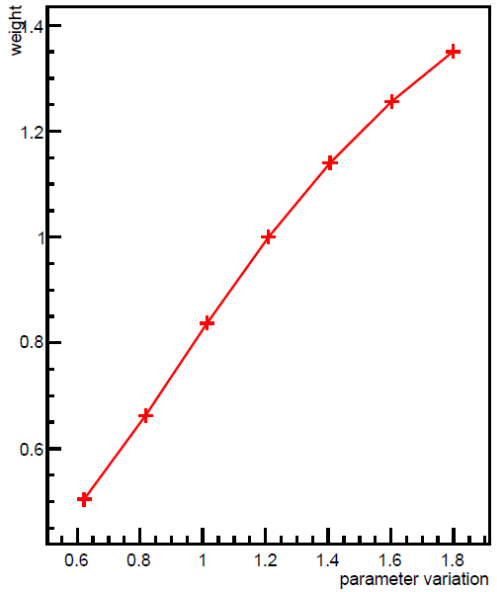
Migration systematics – events can change bins

Result in discontinuous likelihood -> problematic

1D response function



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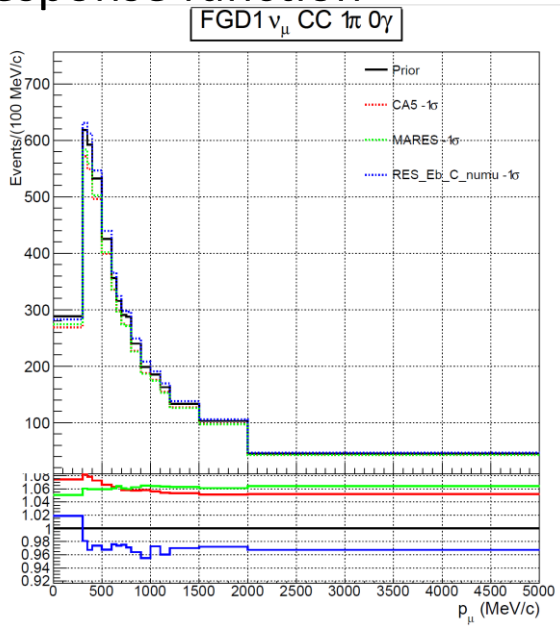
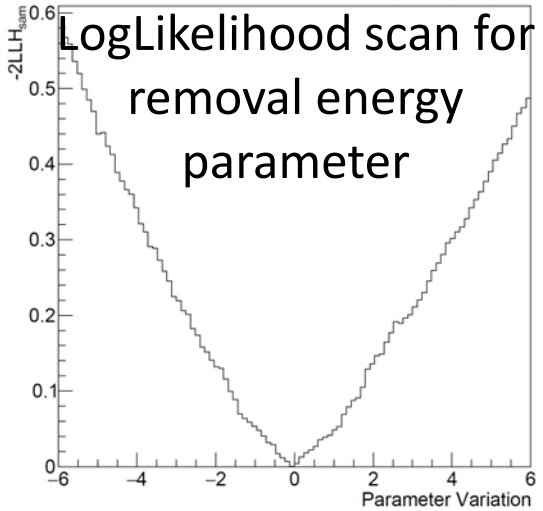


Migration systematic

LogLikelihood scan for removal energy parameter



Outline

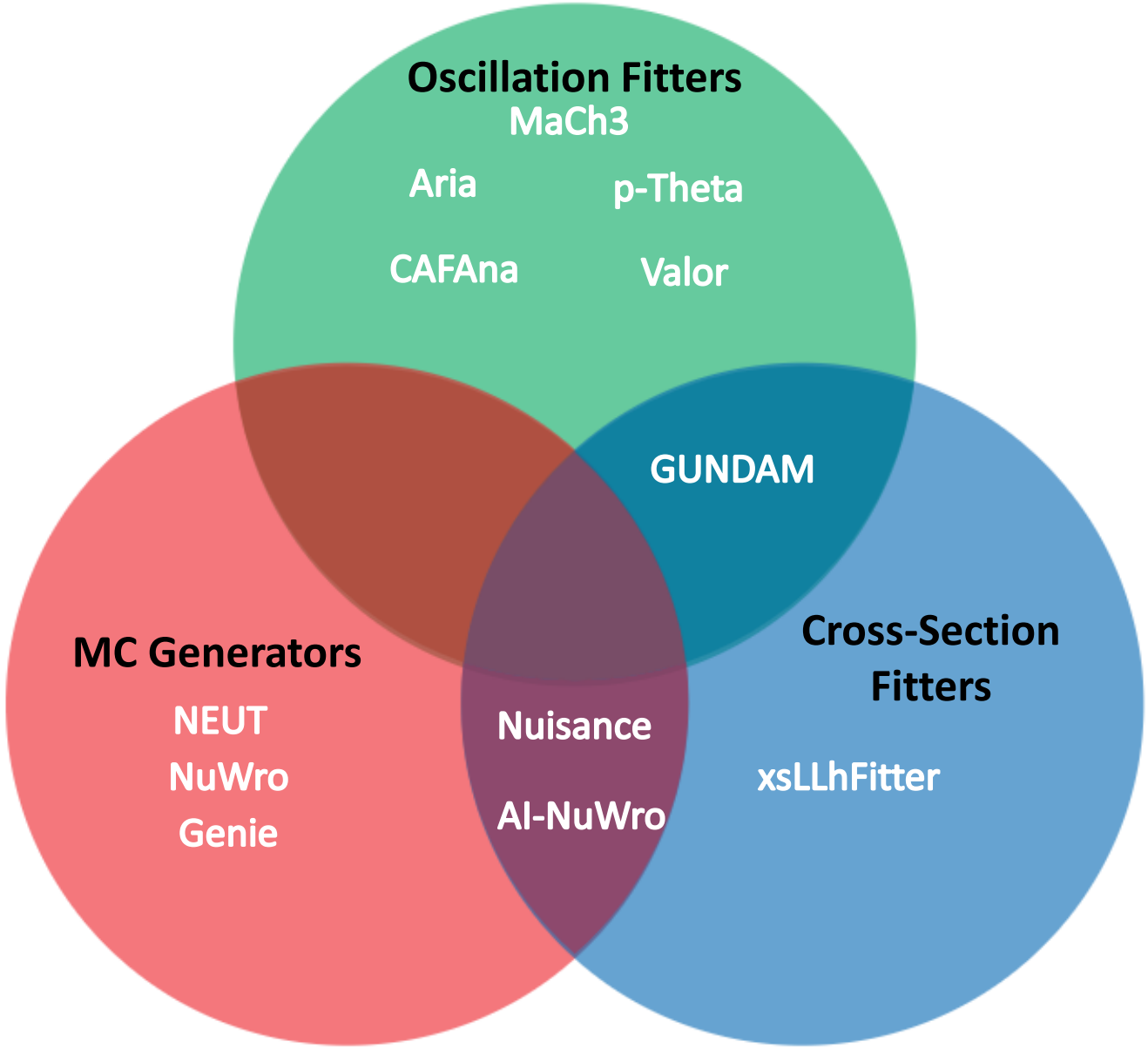
More tools become available.

Classification cross-section or oscillation fitter can be sometimes blurred (apologies for simplification)

How can we solve outlined issues?

Outline

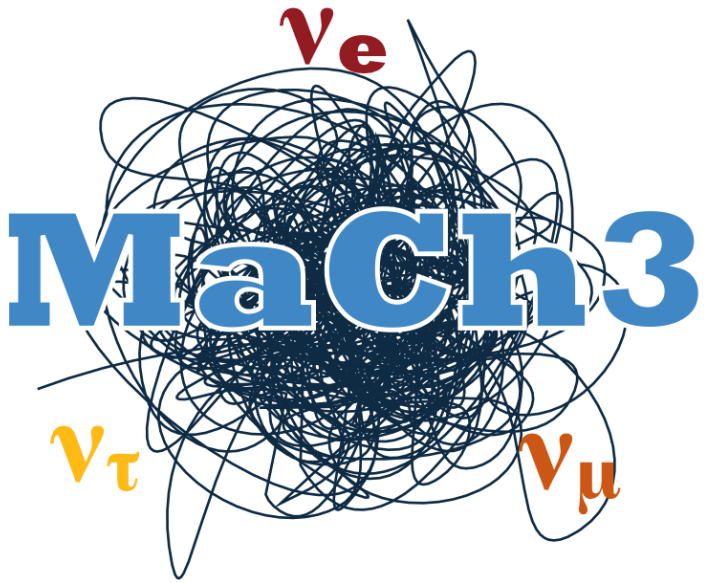
- Oscillation Fitting Tools
  - MaCh3
- Cross-Section Fitting Tools
  - GUNDAM
  - Nuisance
  - AI-NuWro



Oscillation Fitting Tools

MaCh3

MaCh3 is predominantly a **Bayesian Markov Chain Monte Carlo (MCMC)** fitter (there are other fitting algorithms implemented including MINUIT).



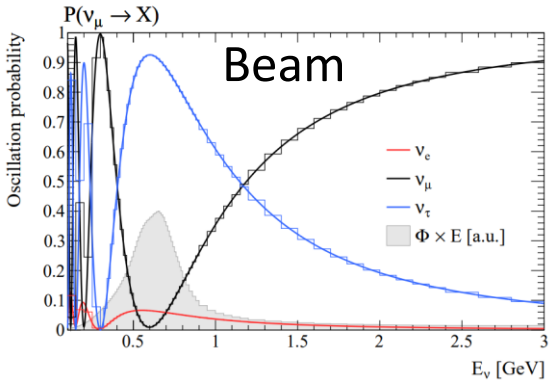
First used by T2K but now by DUNE and HK as well.

Different **MCMC** fitter called Aria is being used by NOvA arXiv:2311.07835

Neutrino Oscillation Calculations

Low dimensional problem but difficult, nonetheless.
Neutrino oscillation calculation can be divided into:

- Beam neutrino calculation - depends only on neutrino Energy, simple



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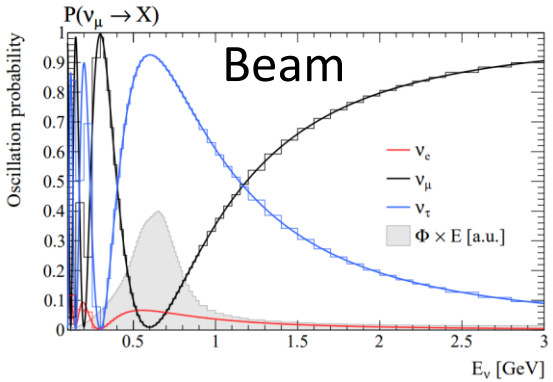
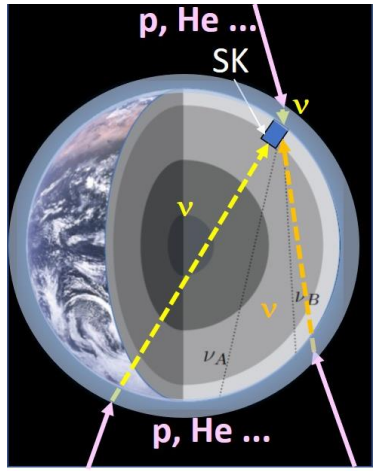
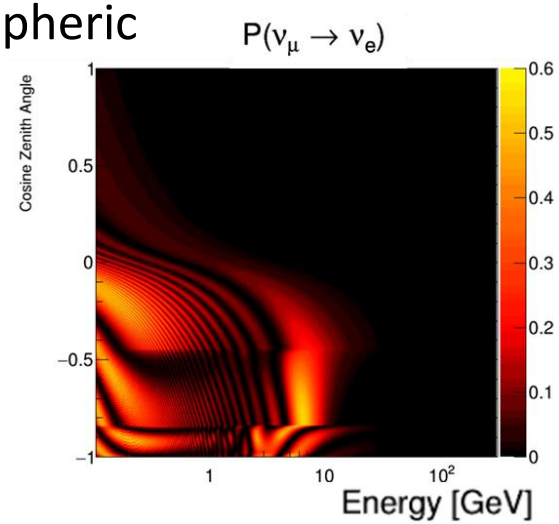


- For Atmospheric neutrinos there is cosine zenith dependence.
  Depending on the angle neutrinos will pass different numbers of earth layers of earth.

Atmospheric





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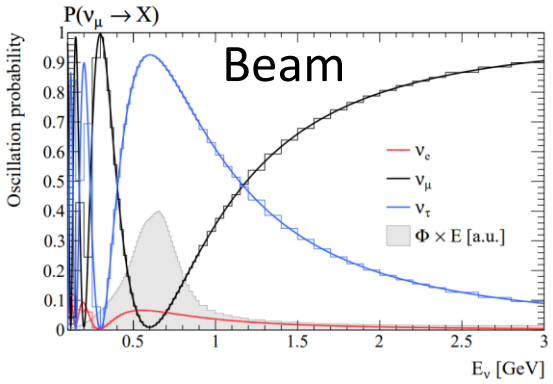

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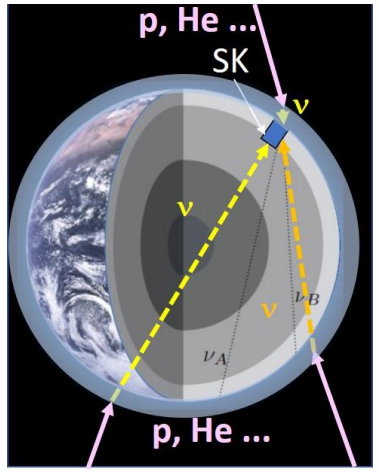
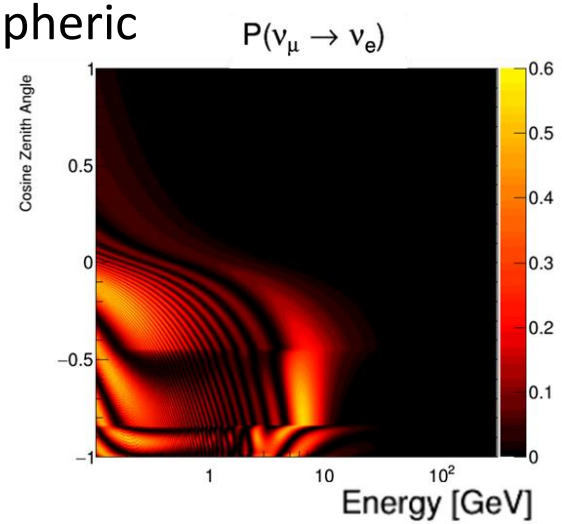
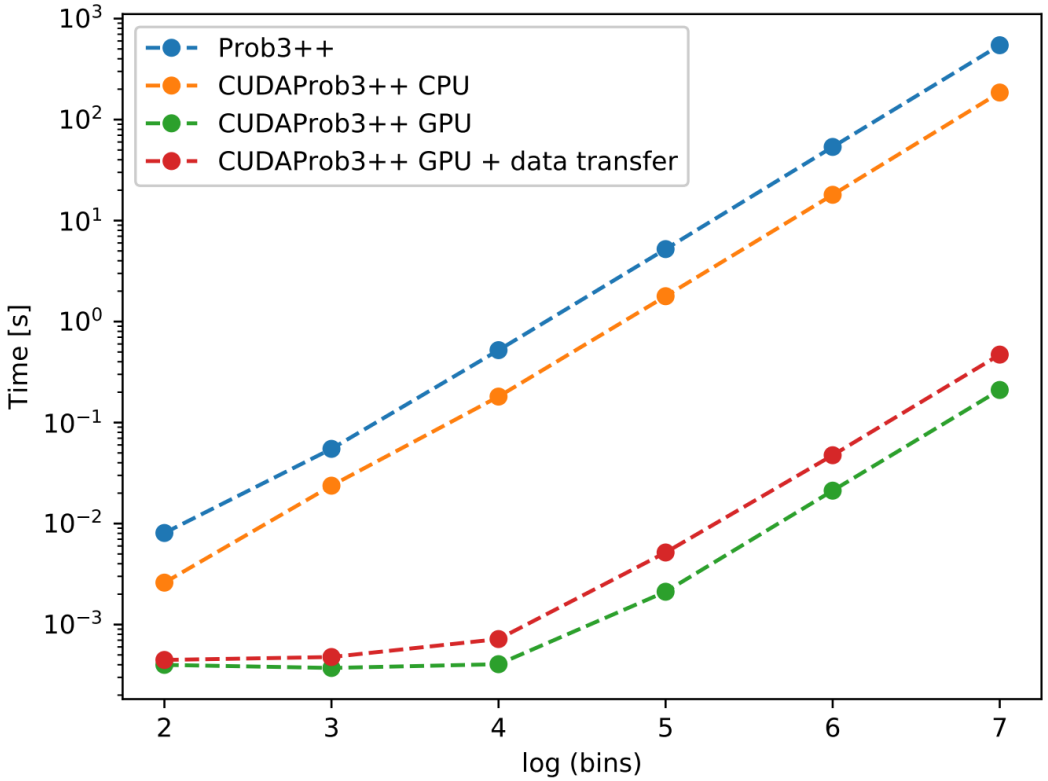




- There are many experiments interested in sterile neutrinos

Oscillators

Oscilator	Hardware	Core language	Flavors	Custom density model	Source
Prob3++	CPU	C++	=3	Yes	
probGPU	GPU	CUDA-C	≥3	No	[1]
CUDAProb3	CPU/GPU	C++/CUDA-C	≥3	Yes	[2]
nuSQuIDS	CPU	C++/Python bindings	≥3	Yes	[3]
CUDAnuSQuIDS	GPU	CUDA-C	≥3	Yes	[4]
GLoBES	CPU	C	≥3	Yes	[5]
NuCraft	CPU	Python	≥3	Yes	[6]
NuFast	CPU	C++/Fortran	=3	No	[7]



doi.org/10.1016/j.cpc.2018.07.022

There are multiple oscillation calculators available.

MaCh3 currently supports **CUDAProb3**, **prob3++** and **probGPU**.

Using **GPUs** can greatly accelerate oscillation computation.

Issues with Multidimensionality

Number of response functions parameters

- T2K 2020 analysis: 18
- T2K 2022 analysis: 48
- T2K 2024 analysis: 160

This can translate to ~**30M** response functions objects. Need to be evaluated at single fit iteration.

Benchmarking MaCh3:

- 2M events
- 160 resp func params
- ~30 M resp func object
- 4200 norm params
- 5 migration params

With 10 years old GPU

Single step 0.05 s
~2M steps in 1d!

MaCh3 uses using custom response function calculation class with GPU acceleration to reduce number of operations.

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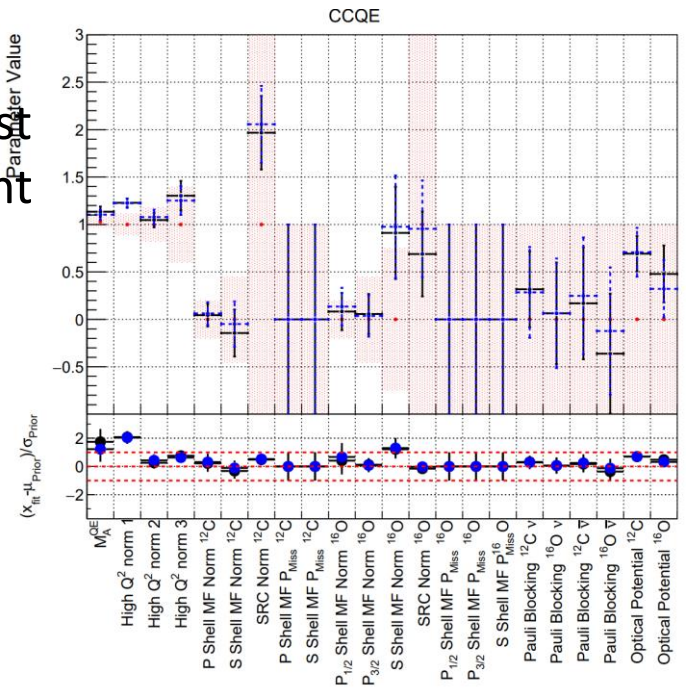
MaCh3 uses using custom response function calculation class with GPU acceleration to reduce number of operations.

Performed fit with 5000 effective parameters.
MCMC scales very well with a number of dimensions.

Fit converged to very similar results.

Comparison of Parameter of interest values using different configuration

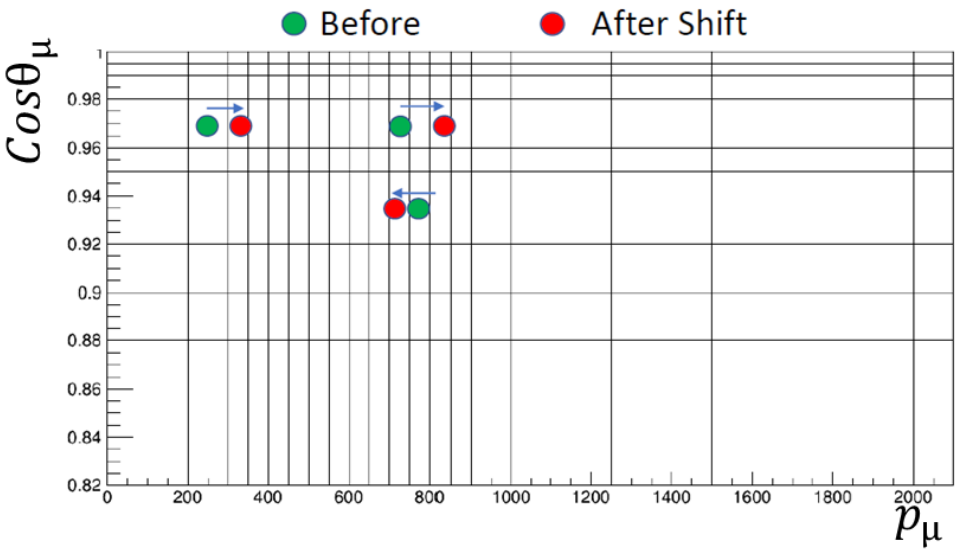


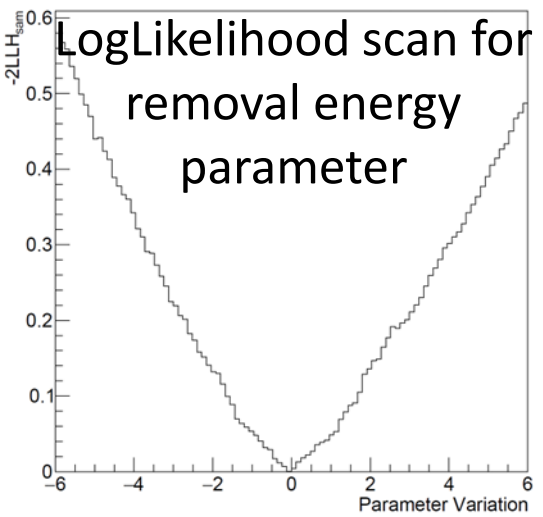
Event Migration – Systematic Uncertainty

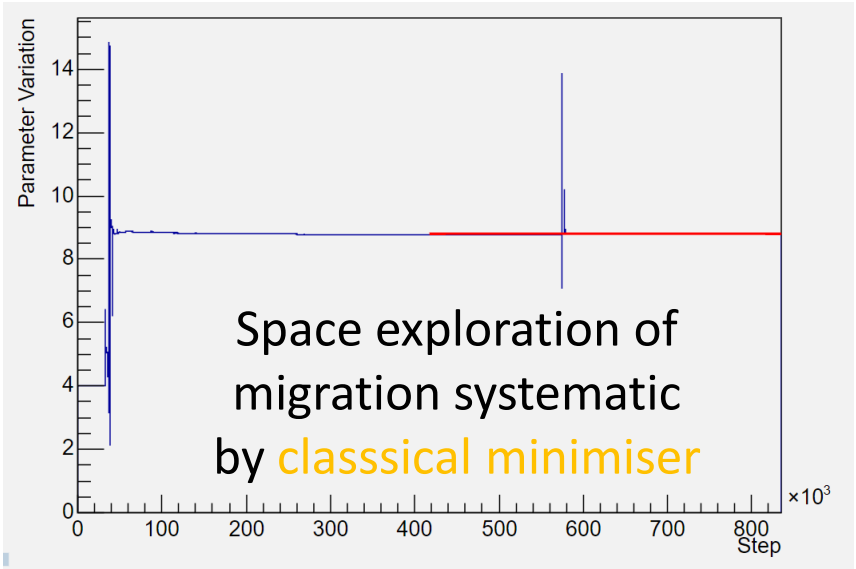
Migration systematic are problematic.

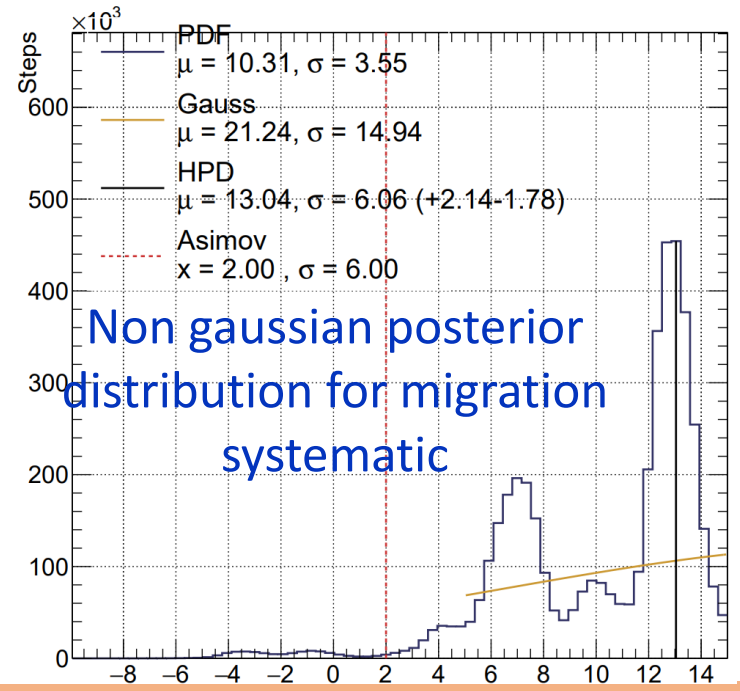
Discontinues likelihood is problematic for many fitting algorithms

A big benefit of the MCMC algorithm is that it can converge even with such problematic implementation.



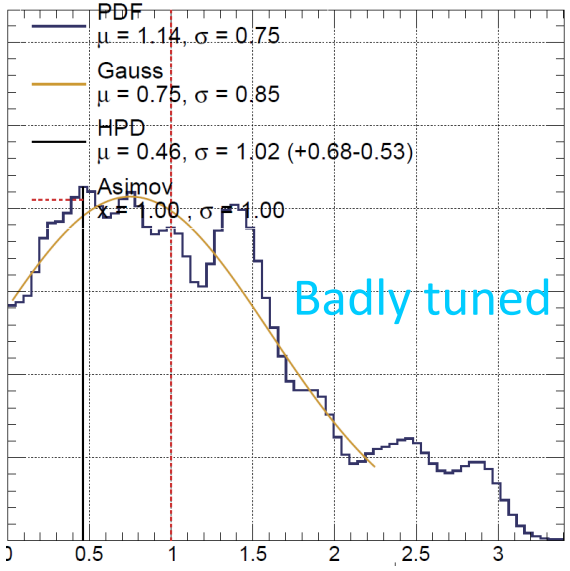


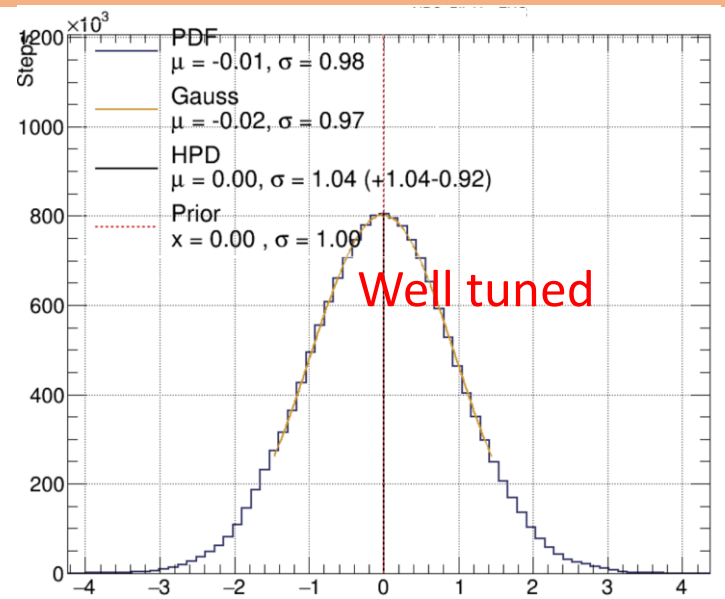




MCMC Diagnostic

MCMC is a powerful tool but can't be treated as a black box



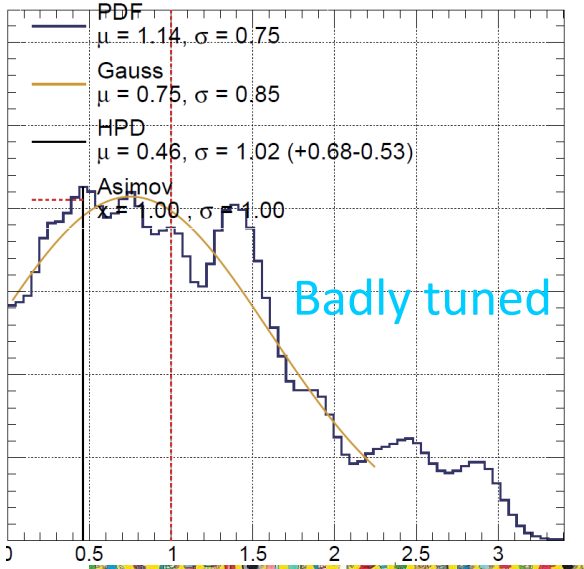


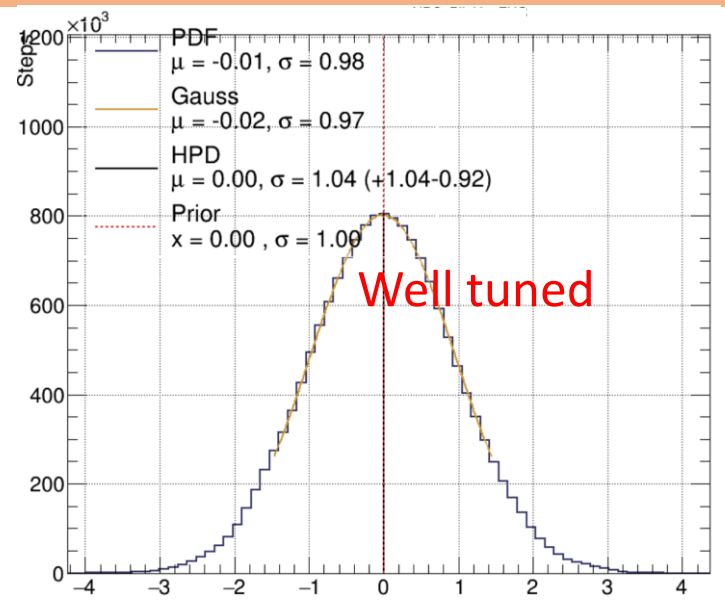
MCMC Diagnostic

MCMC is a powerful tool but can't be treated as a black box

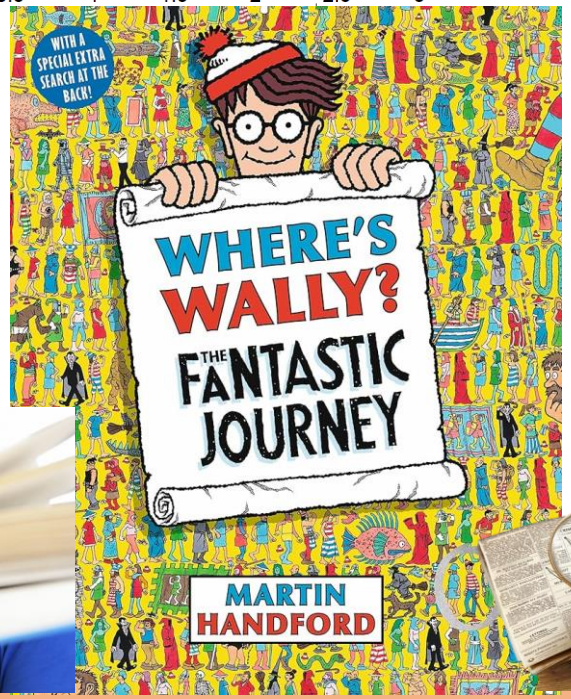
In MCMC you explore phase space my making steps.

Steps are too large or too small inefficient exploration





Large scale



Small scale

MCMC Diagnostic

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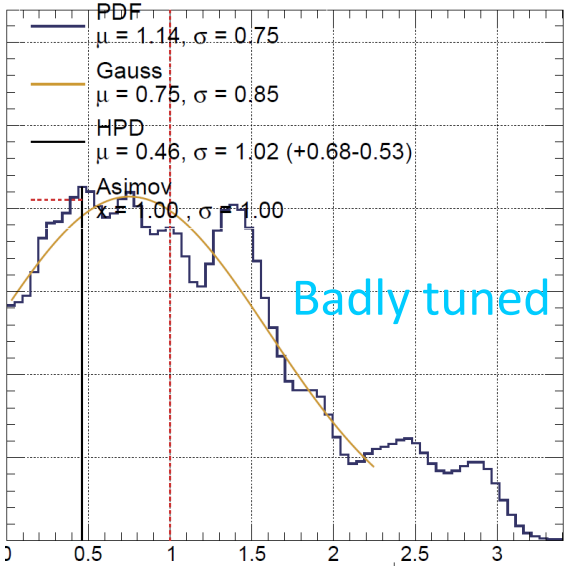
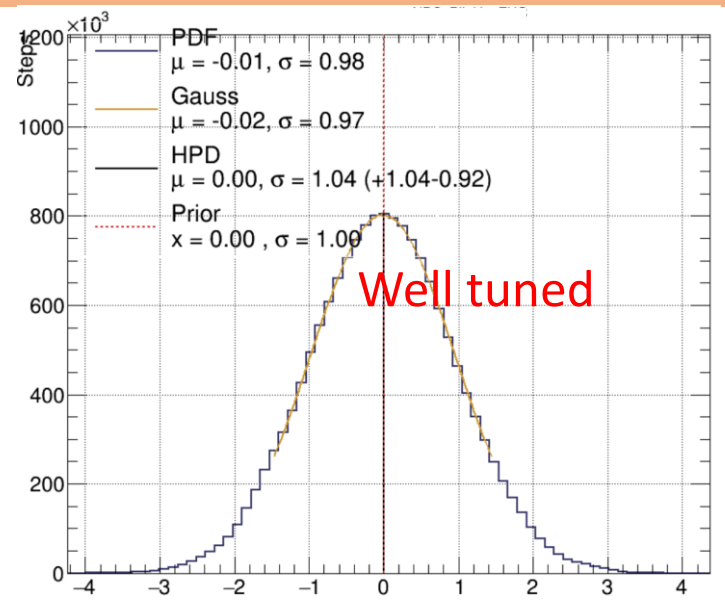
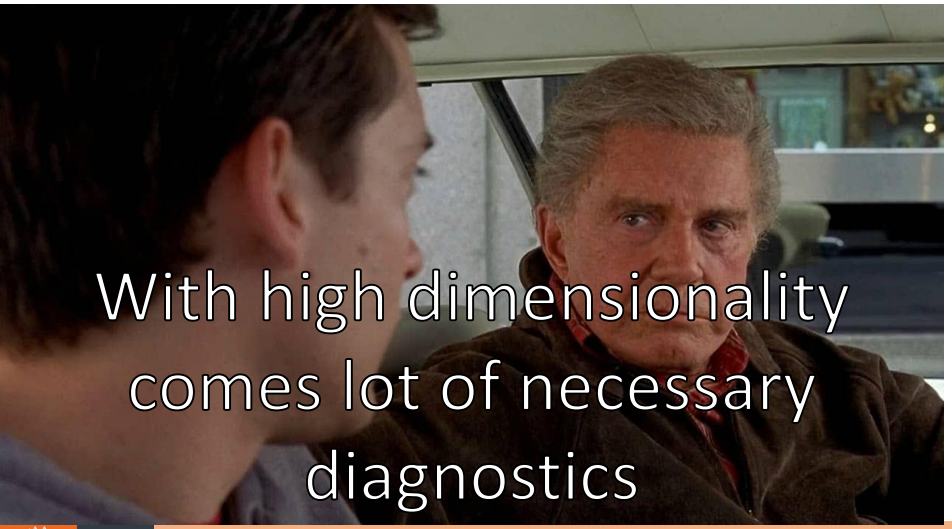
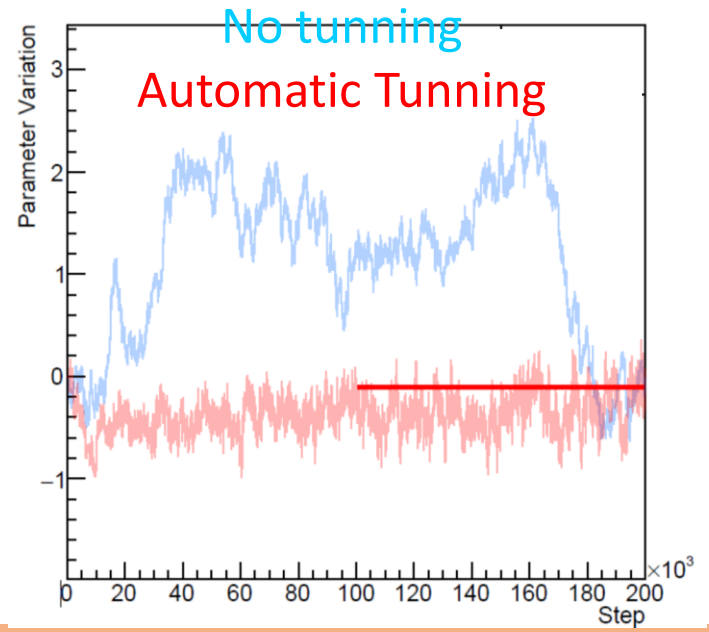
Steps are too large or too small inefficient exploration

We tune MCMC to help with step proposal.
Manual tuning difficult with high dimension
New methods are developed to tune automatically







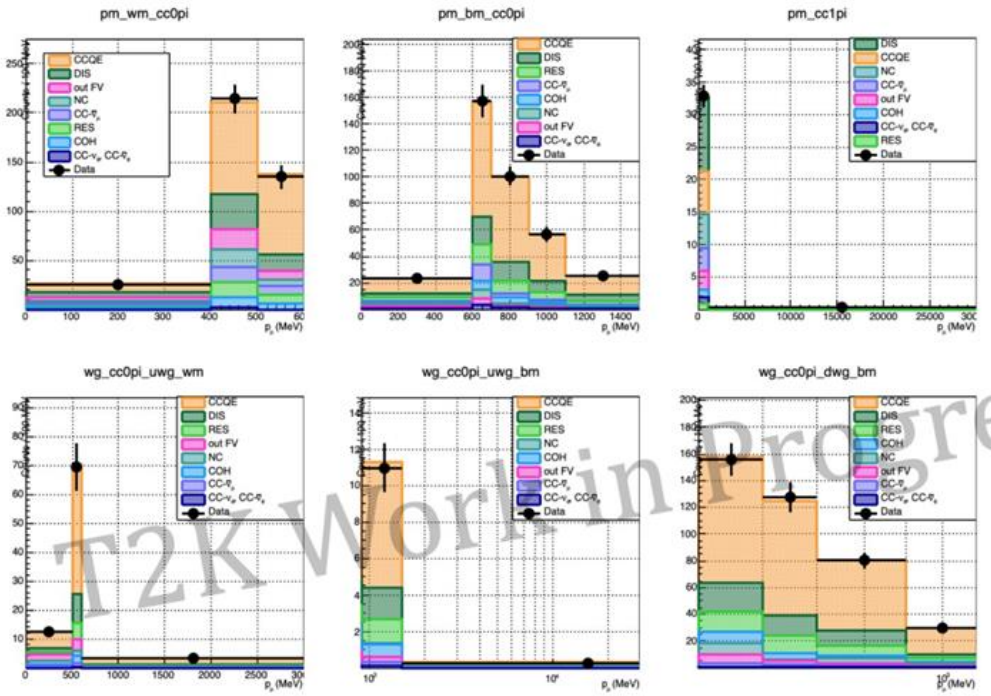


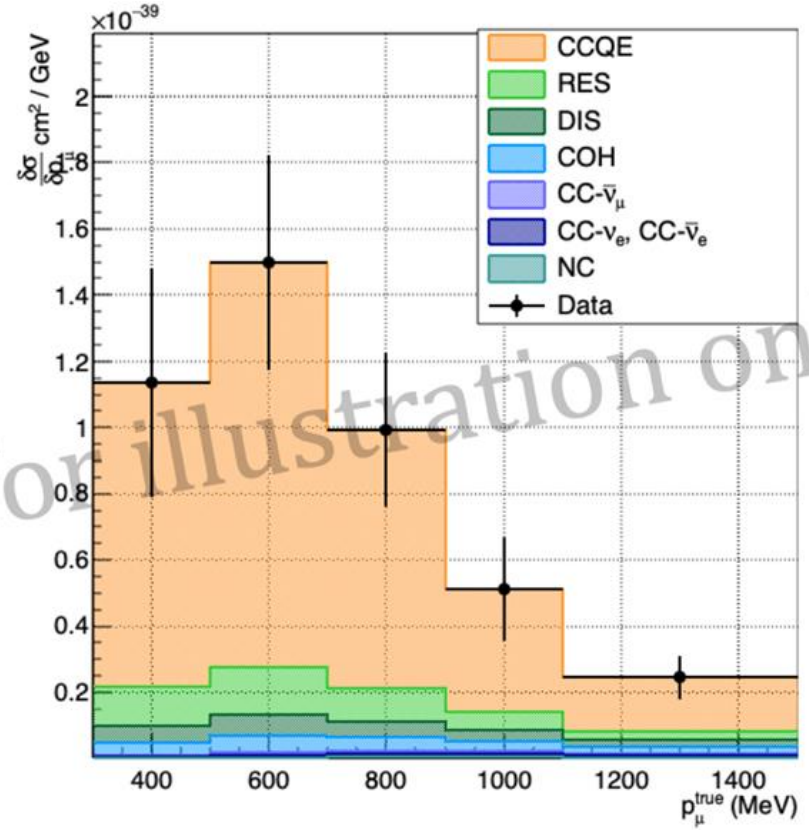
Cross-Section Fitting Tools

GUNDAM

GUNDAM - *Generalized and Unified Neutrino Data Analysis Methods*

Very well optimised with GPU support for response functions.





For more see Laura slides

From event rates → To cross sections

Reducing Dimensionality

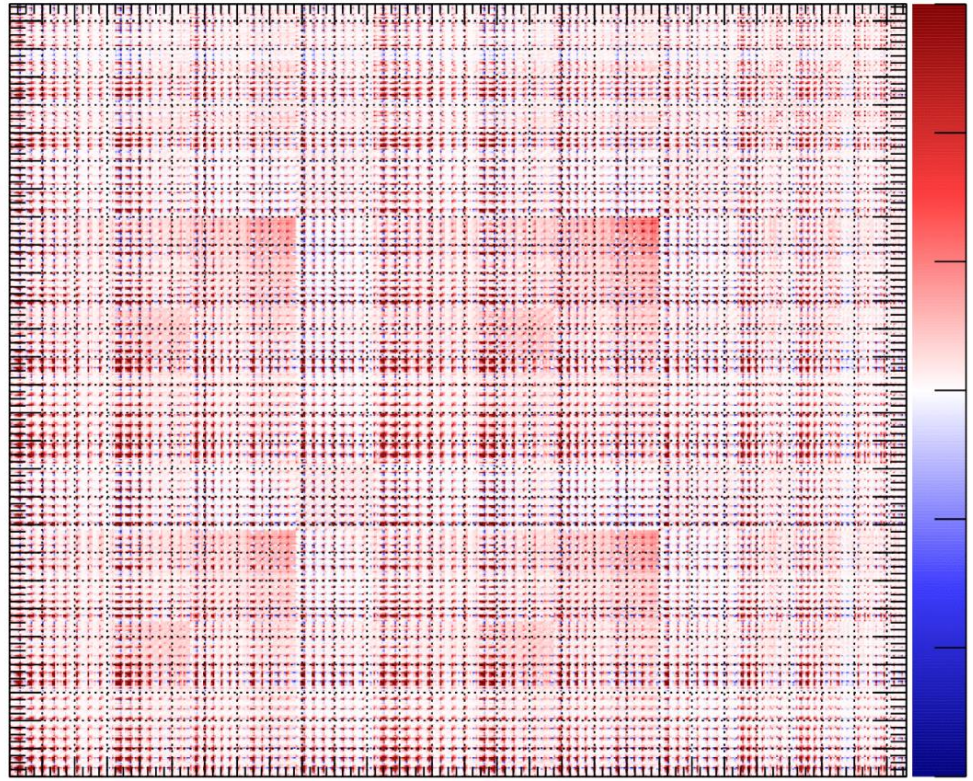
Fight high dimensionality be reducing dimensions

Principal Components Analysis (PCA) allows to reduce dimensionality

removing parameters with very small contribution (eigen value)

Gundam fit converged 12h -> 1-3h

Large highly correlated matrix



For more see Laura slides

Nuisance

Many cross-section measurements done at different channels different experiments etc.

Many neutrino generators available like **NEUT**, **NuWro**, **Genie**, **GiBUU**, **Achilles**.

If you ever wanted to compare your favourite cross-section measurement with your favourite neutrino generator then **Nuisance** the tool just for you.

For more see [Clarence slides Slack]

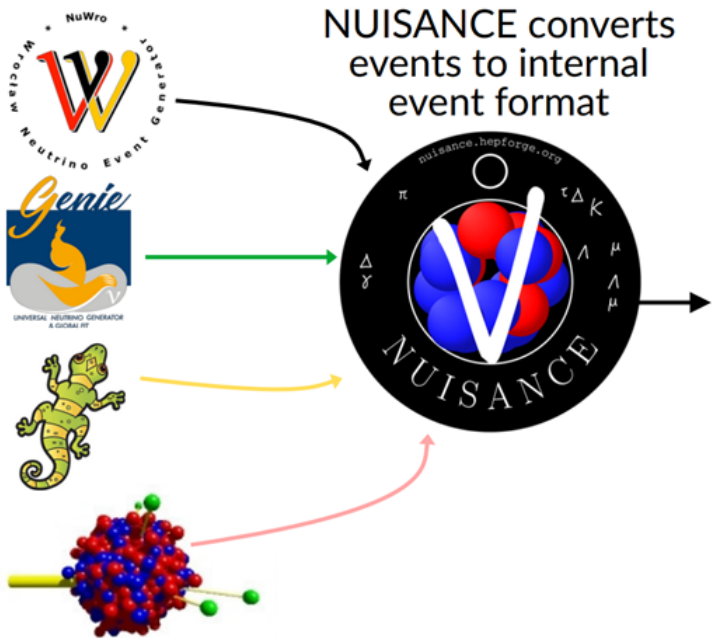
Nuisance

Compare your generators to over **~350 implemented data sets**

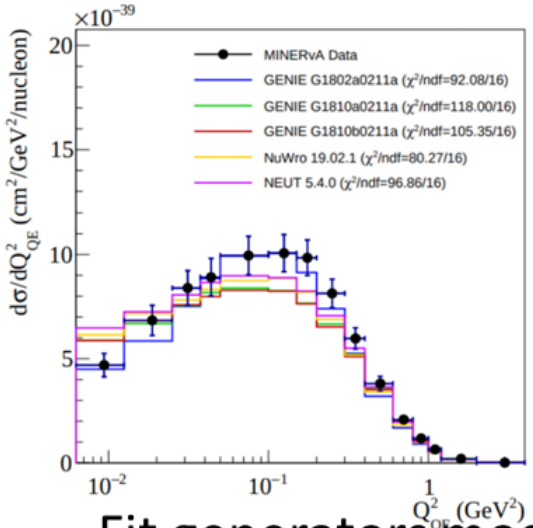
Huge number of combinations

Generate events

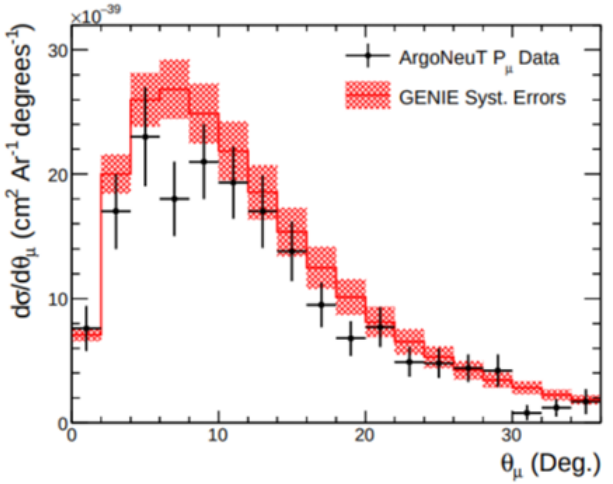
NUISANCE converts events to internal event format



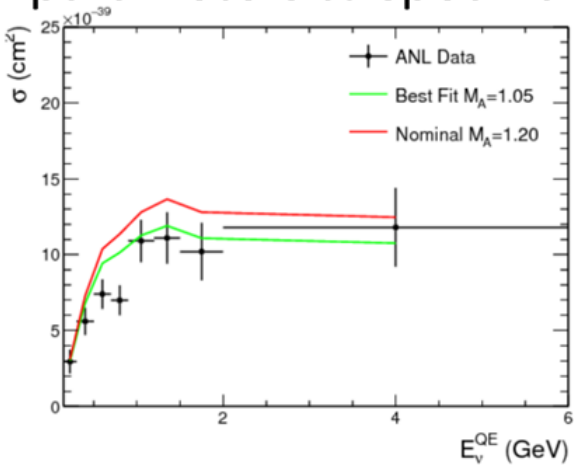
Compare generators to data



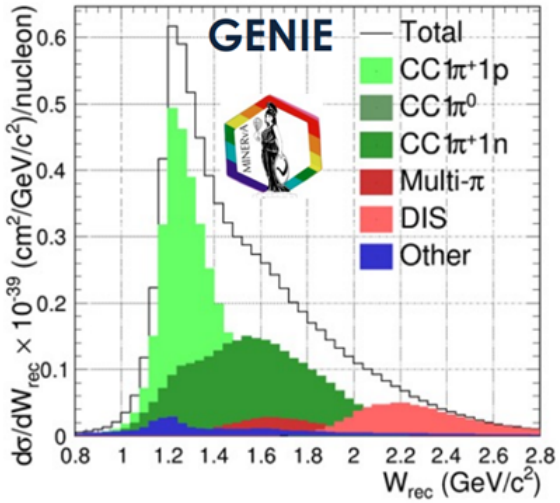
Evaluate uncertainties in model against data



Fit generators model parameters to specific data



Compare generator features



For more see [Clarence slides Slack]

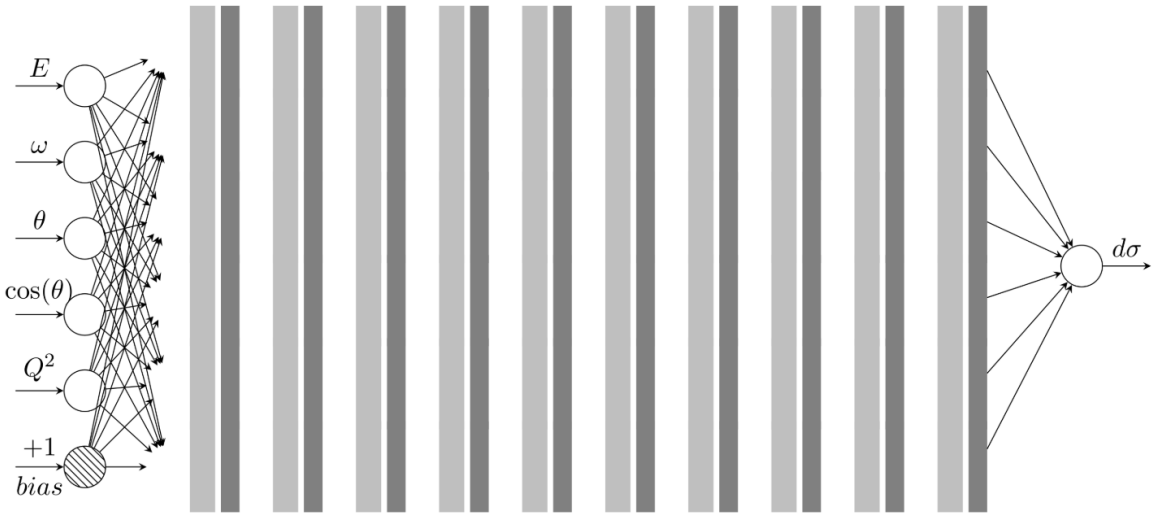
AI-NuWro

Evaluating cross-sections based on electron scattering data using a neural network.

Theoretical models have huge number of parameters.

$$DNN(E,\theta,\omega) \rightarrow \frac{d^2\sigma}{d\cos\theta d\omega}$$

10 blocks, each consists 300 fully connected units and batch normalization layer

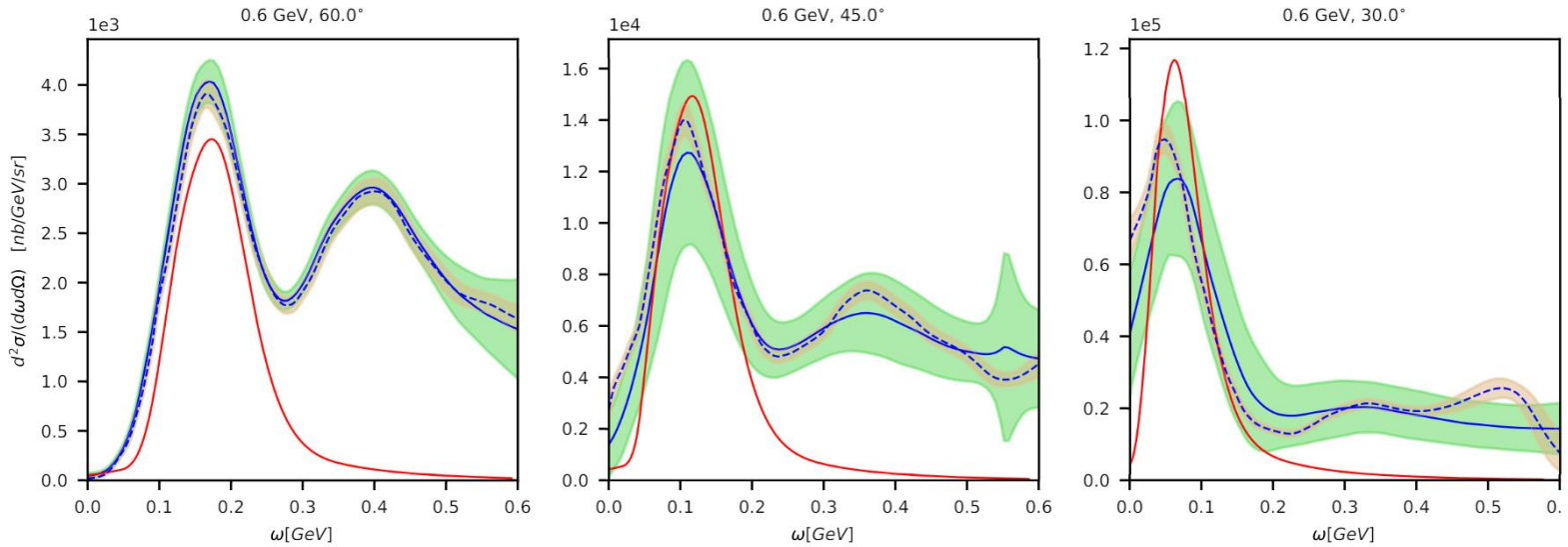


Deep Neural Network (DNN), E = Energy, θ = scattering angle, ω =transfer of energy

Spectral function (theroetical) calculations

Cross-section from DNN

1 sigma error



For more see Krzysztof slides or paper

Summary

Analysis in neutrino becomes more complex and demanding both in terms of computing and analysis choice.

Based on experience from currently running experiments more fitting tools become available for a broader audience.

Common problems like fit convergence, performance and RAM usage
Common tools helps to solve them once and everyone can benefit.

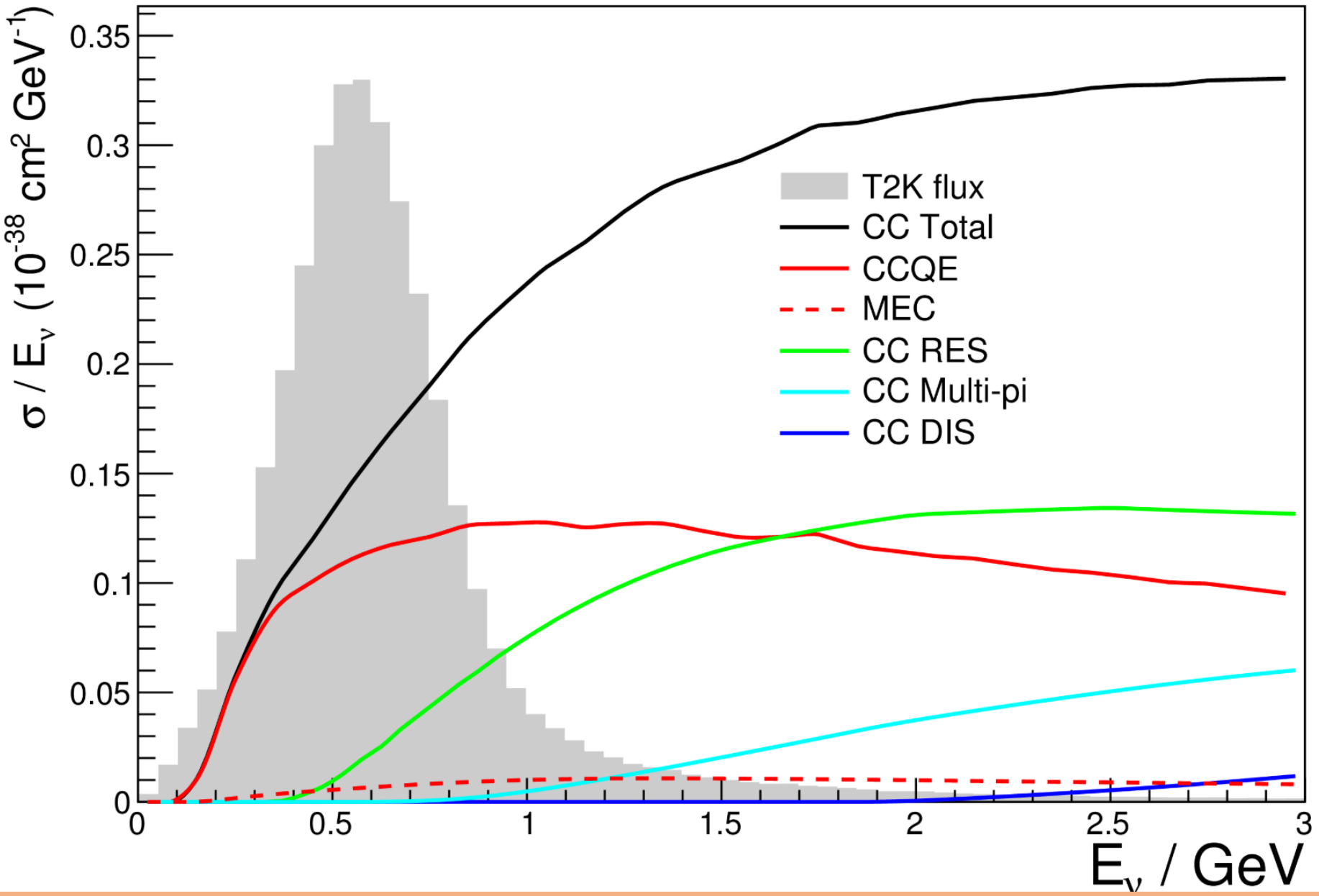
Common tools makes joint-fit in future more easily.

These are exciting times for neutrino physics and happy to be on the isle of Noirmoutier.

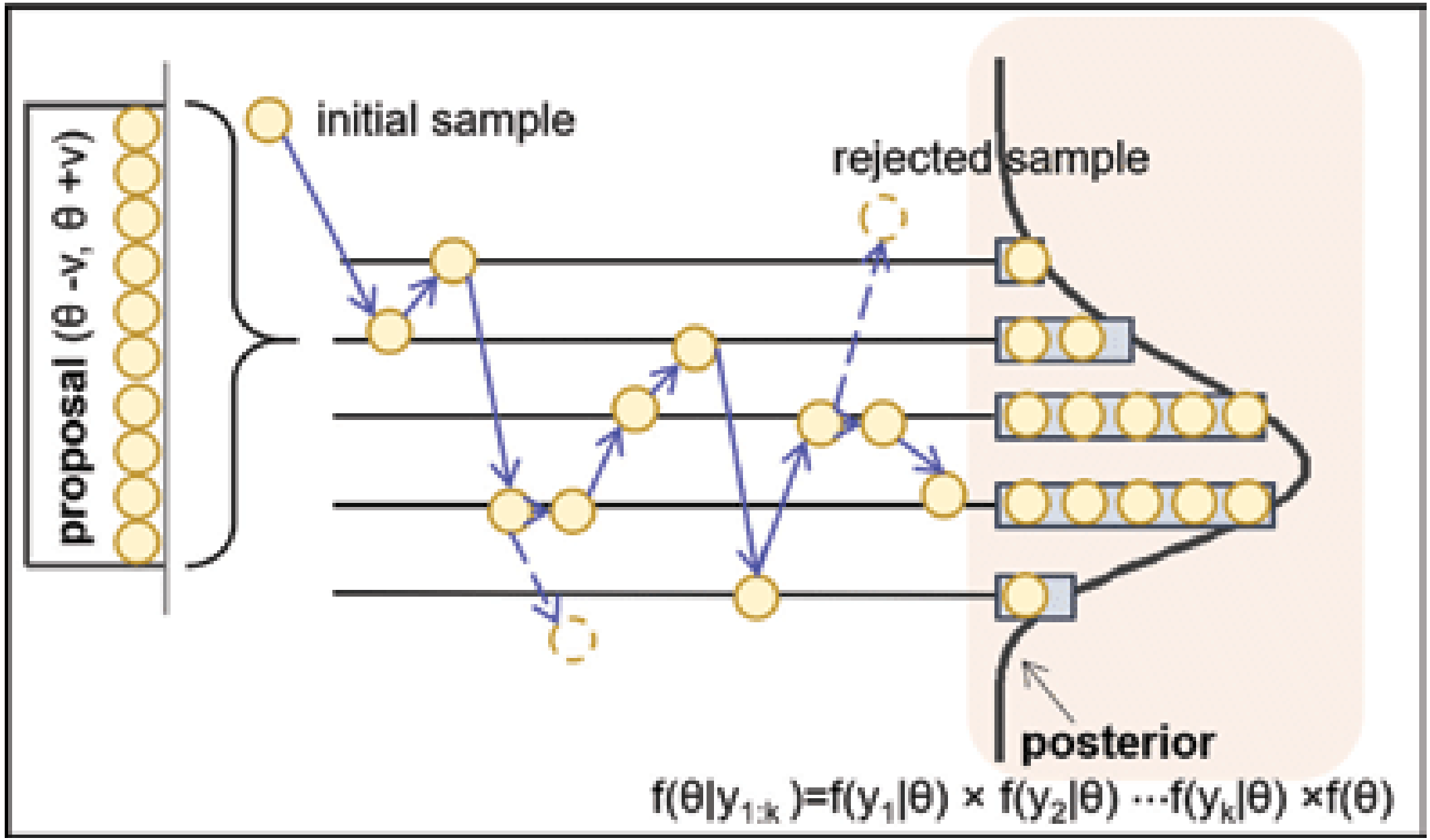
Code Available :
[MaCh3]
[GUNDAM]
[Nuisance]
[Nuisance Tutorial]
[Ai-NuWro]

Backup

Xsec


σ / E$_\nu$ (10^{-38} cm^2 GeV^{-1})
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.5
1
1.5
2
2.5
3
E$_\nu$ / GeV
T2K flux
CC Total
CCQE
MEC
CC RES
CC Multi-pi
CC DIS

MCMC


initial sample
rejected sample
proposal (θ -v, θ +v)
posterior
f(θ|y1:k)=f(y1|θ) × f(y2|θ) ···f(yk|θ) ×f(θ)