



PROfit: A PROfessional, PROficient Framework for Robust Neutrino Parameter Estimation and Optimization



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https://github.com/markrosslonergan/Elephant_Vanishes

What is PROfit?

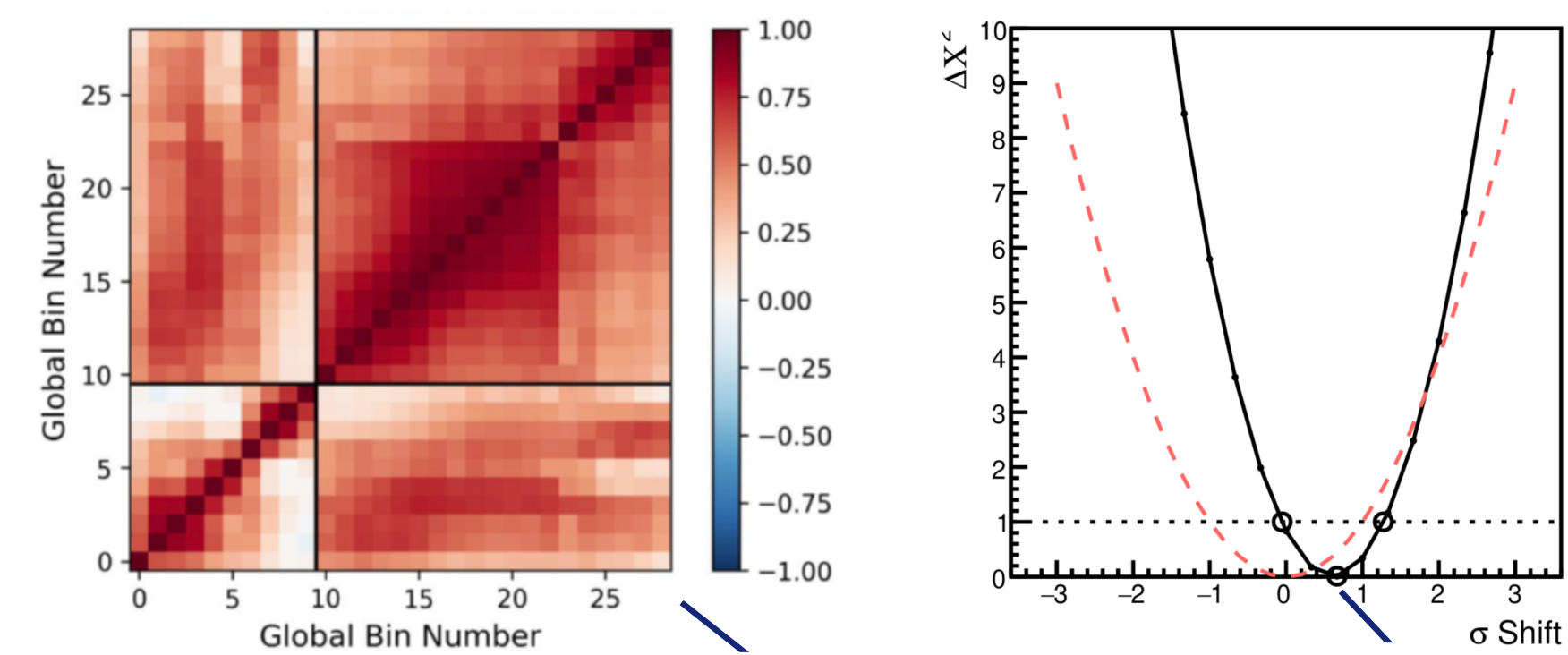
PROfit is a modern framework built with c++ for rapid, robust data fitting, parameter optimization and statistical analysis.

Designed initially for short-baseline sterile neutrino oscillation searches.

Allows for easy run-time configuration of detectors, channels, physics models, and **systematic uncertainties**.

Given data (or fake data) and said systematics, how to fit a given physics model.

- Allows us to understand what the data says about the model (within the systematic uncertainties).



$$\chi^2(\theta, \Delta m^2, \delta_k) = \sum_{i,j} (d_i - p_i) M_{ij}^{-1} (d_j - p_j) + \sum_k \frac{\delta_k^2}{\sigma_k^2}$$

PROfit works to find the set of (physics and nuisance) parameters that **minimizes the χ^2** .

Example Capabilities (representative fake data & toy model)

2 detectors →
4 channels →
(100 bins total)



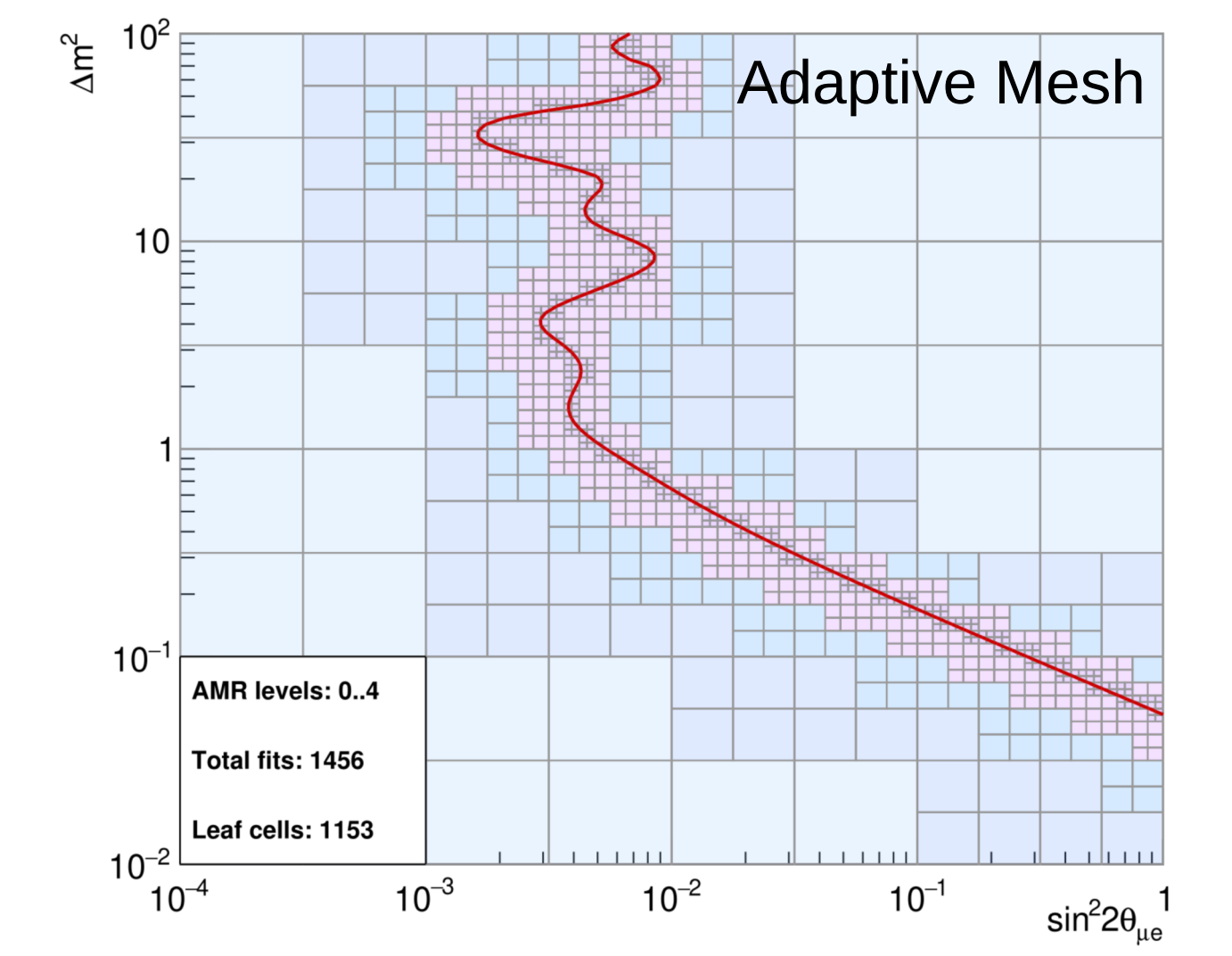
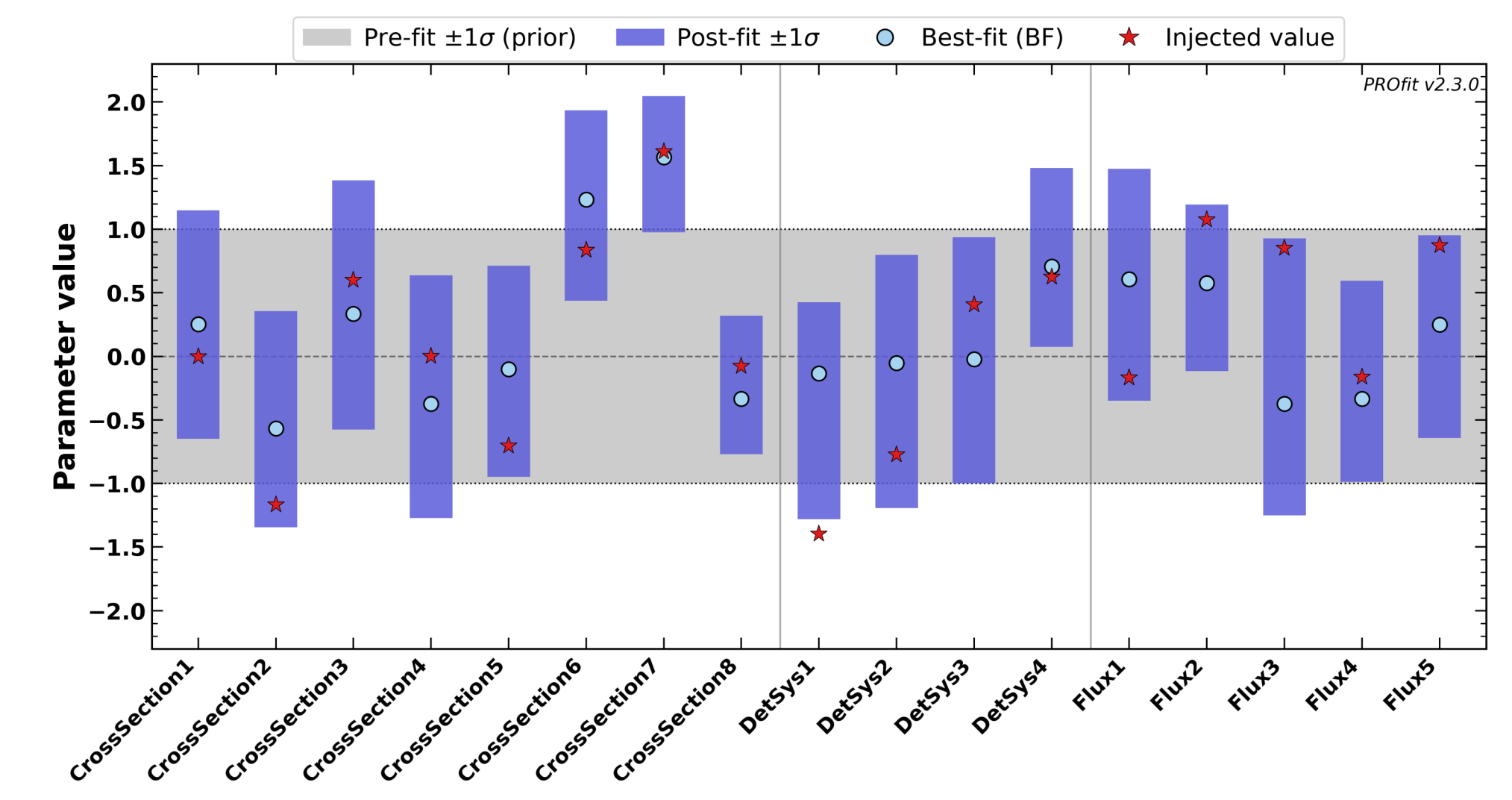
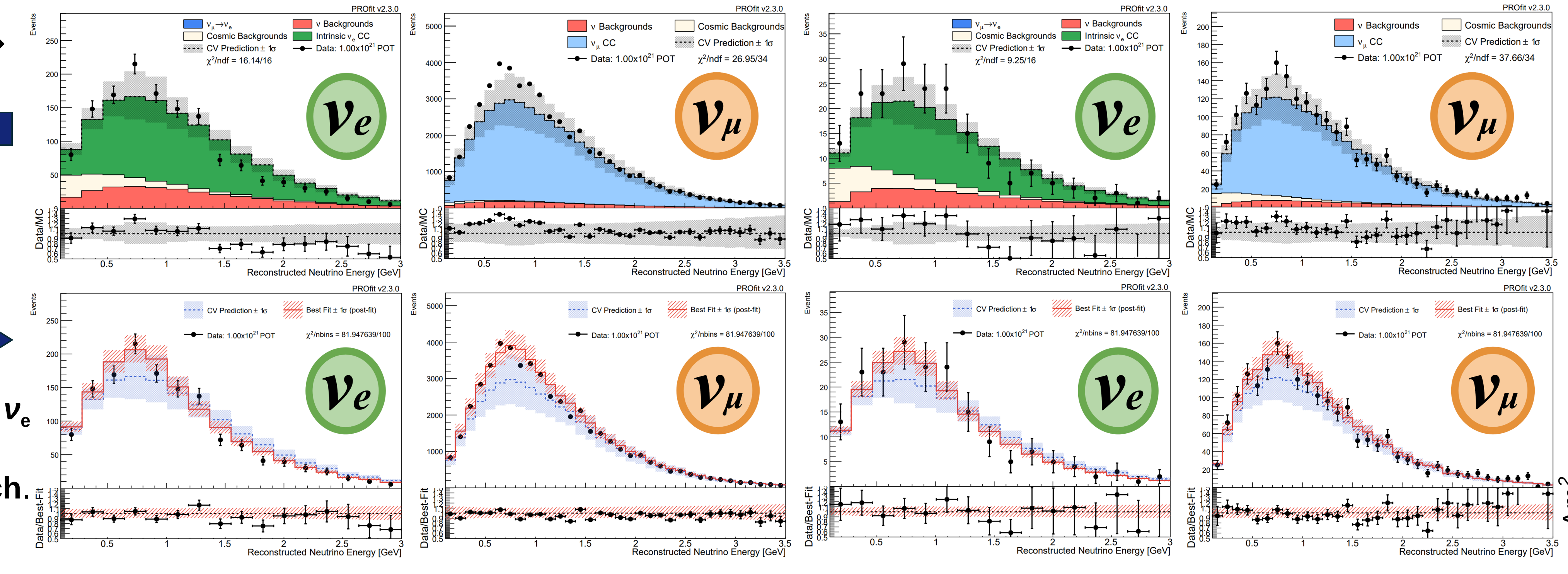
Example of a $\nu_\mu \rightarrow \nu_e$ sterile neutrino appearance search

Toy Model has 17 nuisance systematics and 13 more covariance systematics.

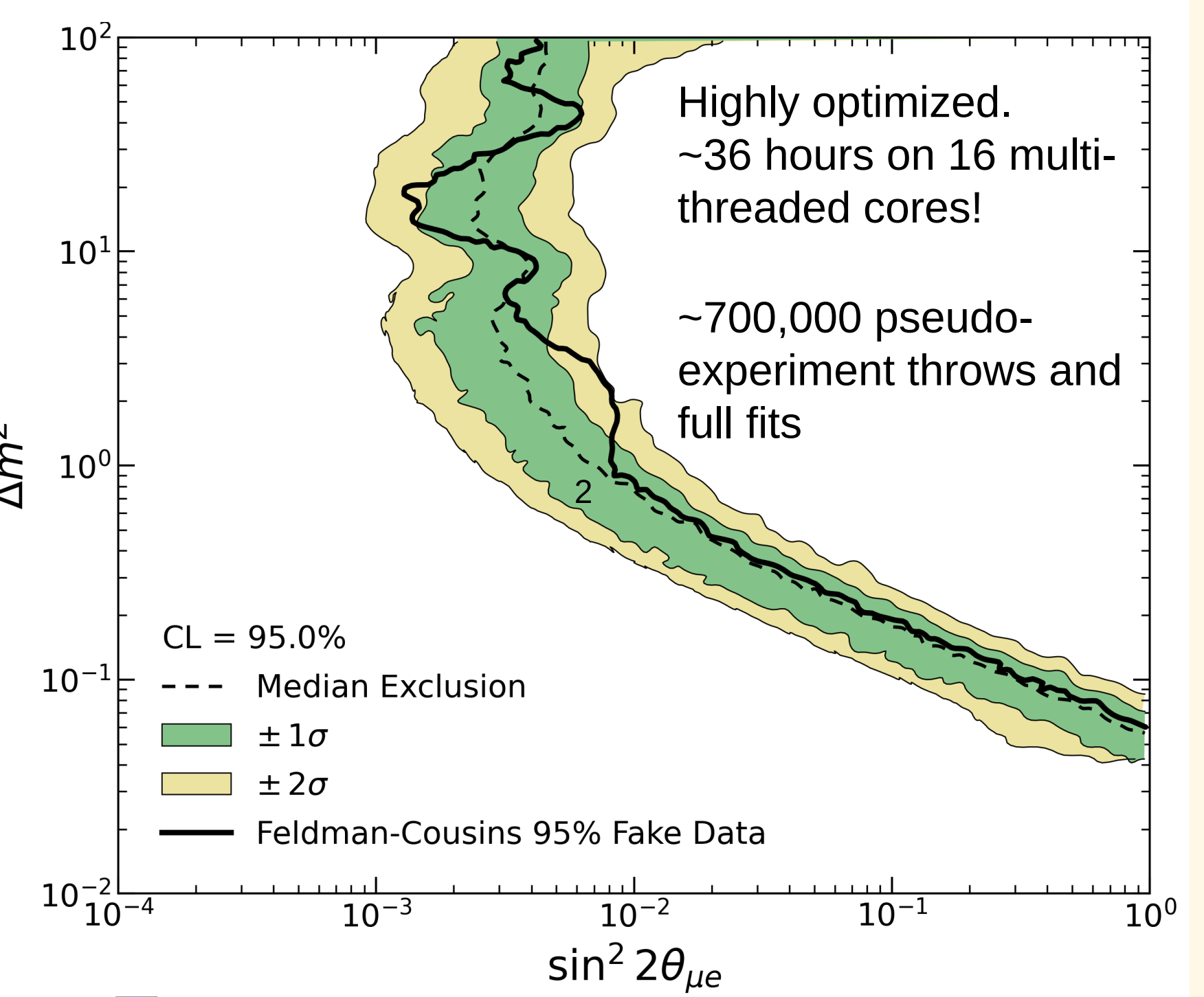
Detailed analysis of the resulting pulls to the nuisance parameters, recovering fake data.

Near Detector

Far Detector



- Post-fit shows good agreement between Monte Carlo and data.
- No evidence of sterile neutrinos in this test (None-injected).
- Use gold standard **Feldman-Cousins^[1]** to draw **Brazil band sensitivity** and **FC exclusion regions!**



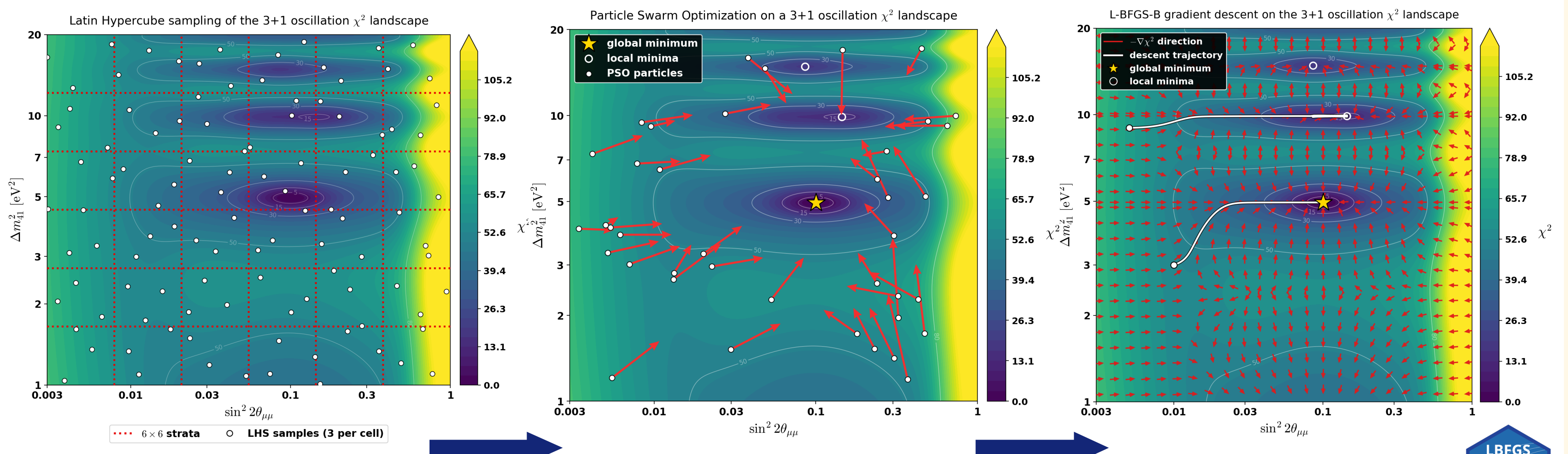
Highly optimized. ~36 hours on 16 multi-threaded cores!
~700,000 pseudo-experiment throws and full fits

CL = 95.0%
--- Median Exclusion
--- ± 1σ
--- ± 2σ
--- Feldman-Cousins 95% Fake Data

← **Adaptive Feldman-Cousins** procedure uses both **adaptive meshing** to focus on regions of interest, as well as identifying number of pseudo-experiment throws needed for given CL.

How to Minimize PROfit

Goal is to find the minimum χ^2 , but physics parameters may be highly degenerate and nuisance parameters form an extremely high dimensional space (~100's of nuisance parameters).



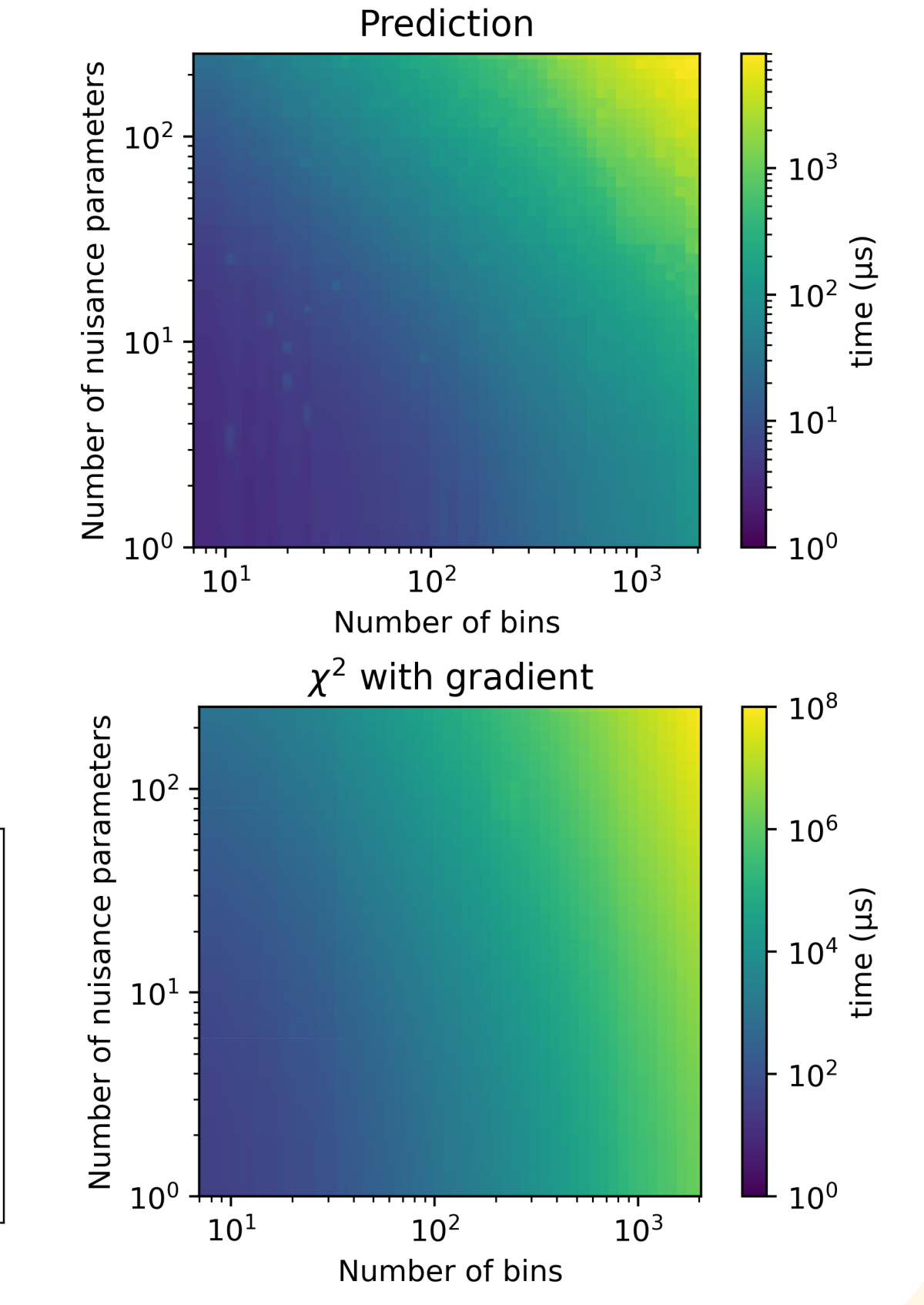
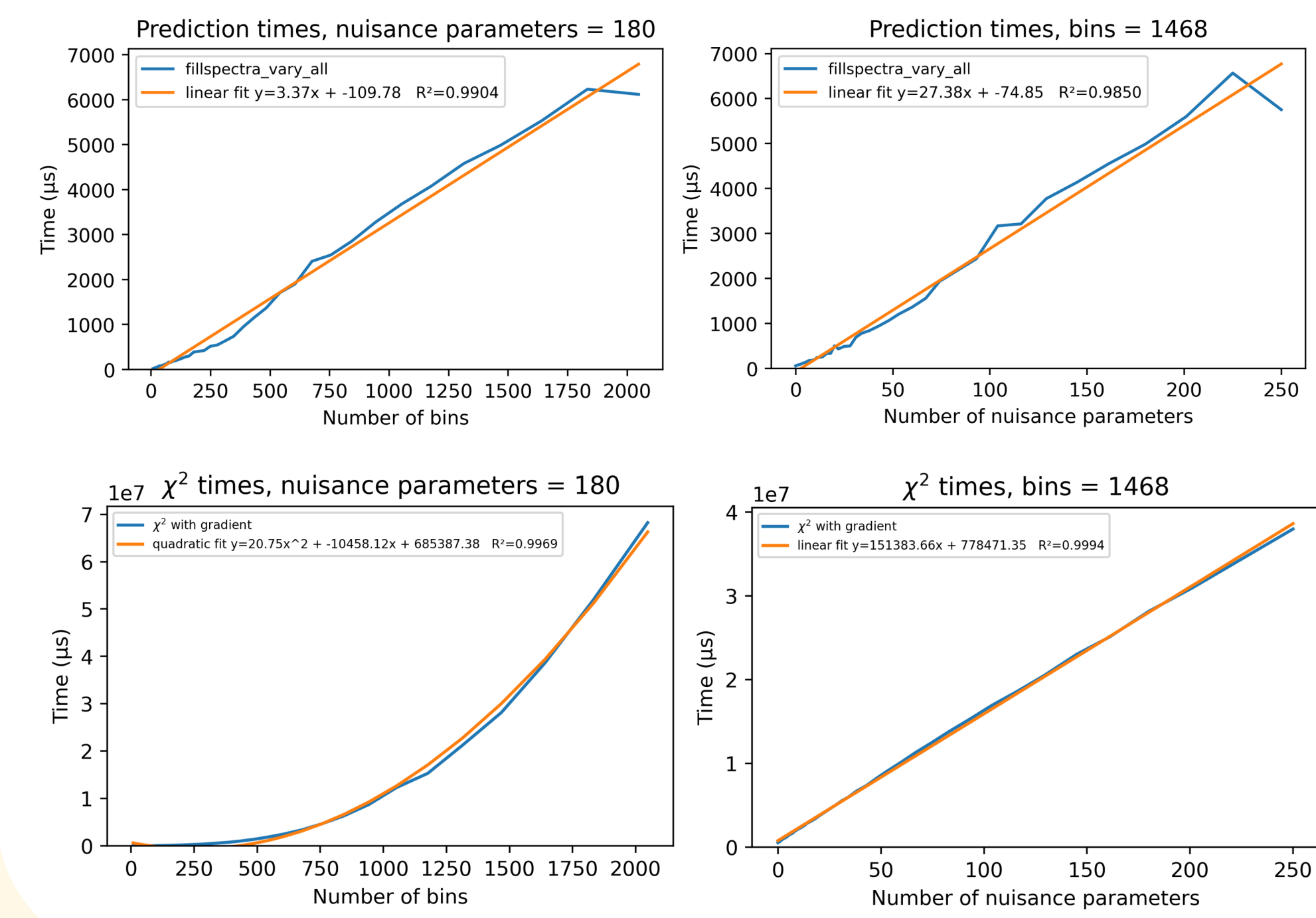
- Latin Hypercube** sampling to get uniform distribution across all physics and nuisance parameters.
- Particle Swarm Optimization** seeded by best Latin hypercube points. Goal is to roughly find all local minima.
- Gradient based L-BFGS-B Minimization** using LBFSGS++ package^[2] to find precise global minima, seeded by particle swarm.

4. **Harmonic Seeding:** Degenerate Δm^2 harmonics are pre-identified and kept as seeds, so the fit tracks the true global minimum even when a systematic shift swaps which harmonic is deepest.

$$P(\nu_\mu \rightarrow \nu_e) \propto \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \approx \sin^2\left(\frac{\Delta m_N^2 L}{4E_\nu}\right), \quad \Delta m_N^2 = \Delta m^2 + \frac{4\pi E_\nu}{L}$$

Scaling and Performance

For n bins and m nuisance parameters, generating a prediction scales as $O(nm)$ and calculating the χ^2 and gradient scales as $O(n^2 + nm)$.

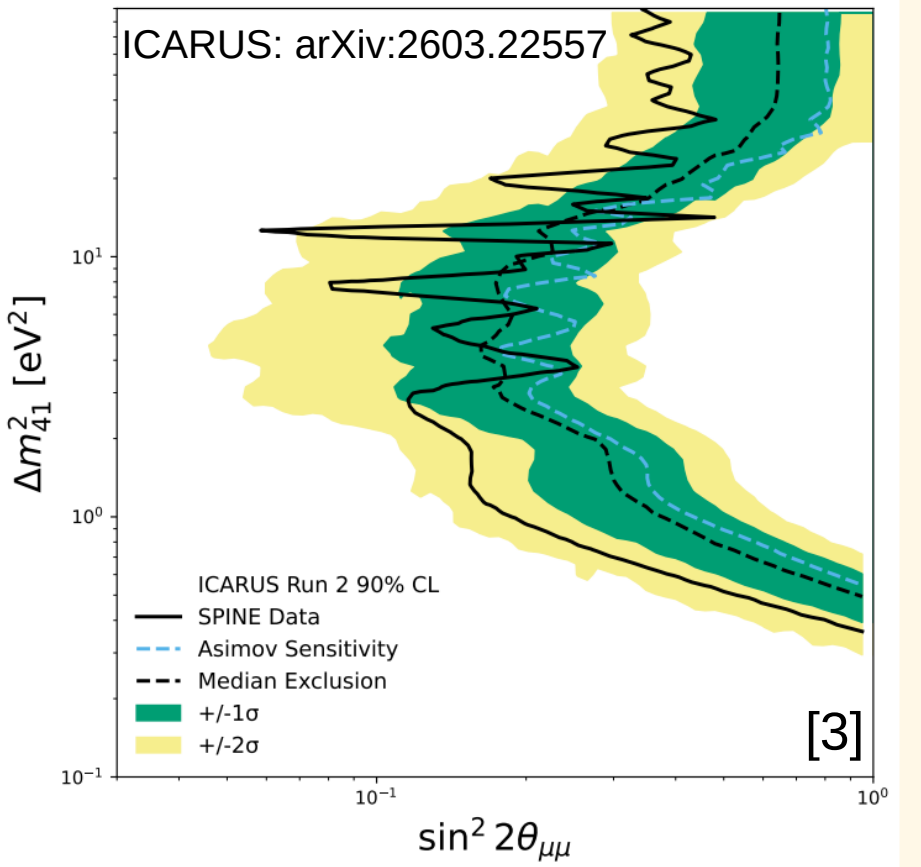


Enabling Physics

First physics result using PROfit was for ICARUS ν_μ disappearance.

Currently being used in:

- MicroBoONE
- SBND
- ICARUS
- Combined SBN
- DUNE



Existing Physics Models and Features:

- 3+1 and 3+2 light sterile oscillations
- 3+1+invisible decay (*Visible decay coming soon*)
- Long baseline oscillations (with NuFast^[4])
- BSM template fits
- 2D Fits (e.g. energy and angle) to take advantage of SBND/DUNE PRISM effects

[1] Feldman-Cousins: Phys. Rev. D 57, 3873 (1998)
[2] LBFSGS++: <https://github.com/yixuan/LBFSGSpp/>
[3] ICARUS: arXiv:2603.22557 [hep-ex]
[4] NuFast: arXiv:2511.04735, arXiv:2405.02400 [hep-ph]
[5] SBNFit: arXiv:2002.07858 [physics.comp-ph]

