Accelerating Calculation of Confidence Intervals for NOvA's Neutrino Oscillation Parameter Estimation with Supercomputers

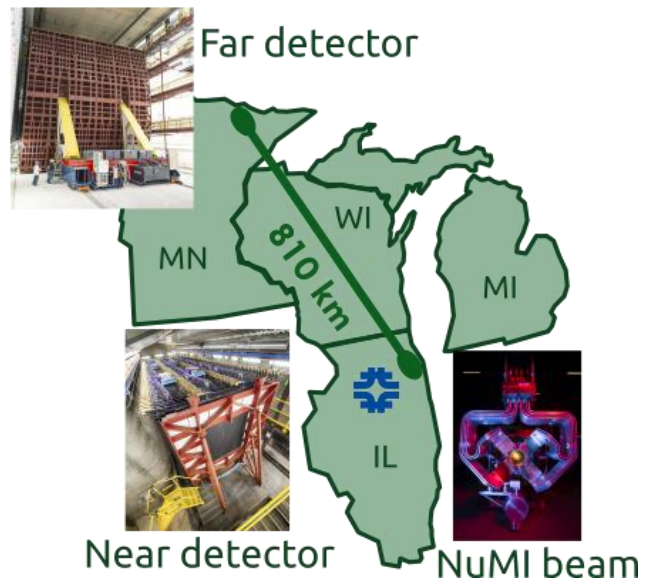
Steven Calvez[1], Tarak Thakore[2] on behalf of the NOvA and SciDAC-4: HEP Data Analytics on HPC collaborations

[1]Colorado State University, [2]University of Cincinnati

The NOvA Experiment

NOvA [1] is a **long-baseline neutrino oscillation experiment** aiming to determine :

- Neutrino **mass hierarchy**
- Neutrino **oscillation parameters**
- CP violating phase δ_{CP}
- Searching **for sterile neutrinos** and other **Beyond the Standard Model** physics models



Feldman-Cousins Unified Approach

Compare data and **prediction** for a given set of oscillation param. using a **negative log-likelihood** and relate it to a **chi-square distribution** $\chi^2 = -2logL(\vec{\theta})$

Build a **test statistic** $\Delta\chi^2 = \chi^2(\vec{\theta}) - \chi^2(\overrightarrow{\theta_{best}})$ comparing the best fit point $\overrightarrow{\theta_{best}}$ to the best fit for a given set of parameters $\vec{\theta}$

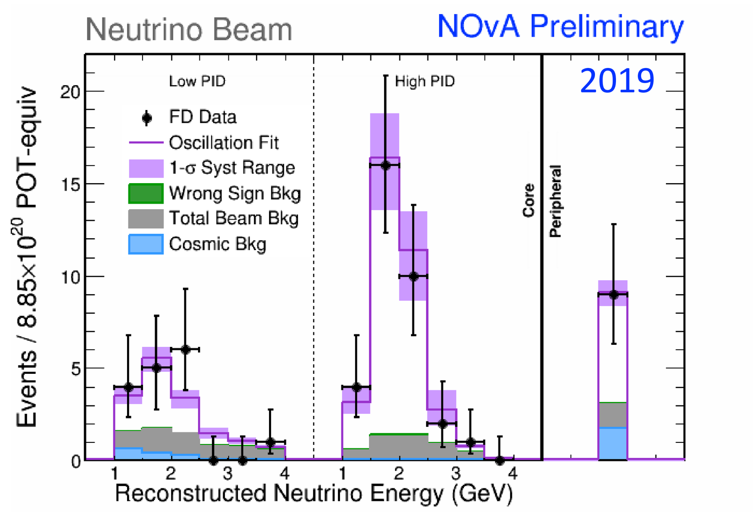
Compute a ***p*-value** analytically (Wilks' theorem) and derive a **significance**

Low statistics + param. with physical boundaries ≠ Wilks' theorem

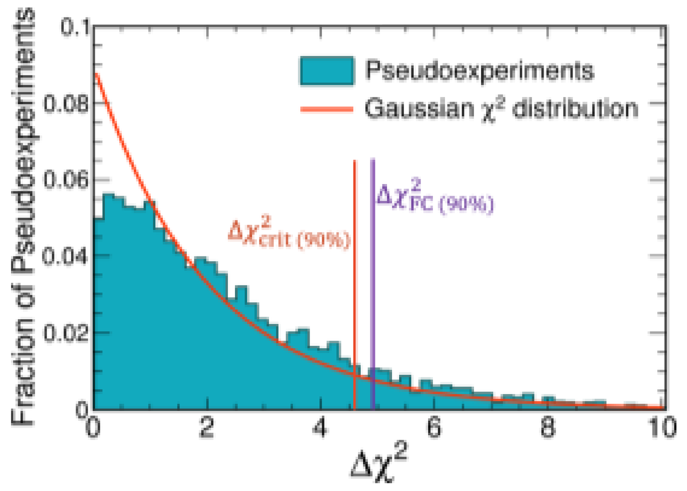
Generate and fit thousands of **pseudoexperiments** to **empirically build** a $\Delta\chi^2$ distribution for each point of the parameter space

Compute the **fraction of pseudoexperiments** with a $\Delta\chi^2$ larger than the one observed in data

Compute a **significance** from that ***p*-value**



Electron neutrino candidates spectra in NOvA's Far Detector



Corrected statistical coverage with the Feldman-Cousins approach [3]

Statistical Coverage for Neutrino Oscillation Parameter Estimation

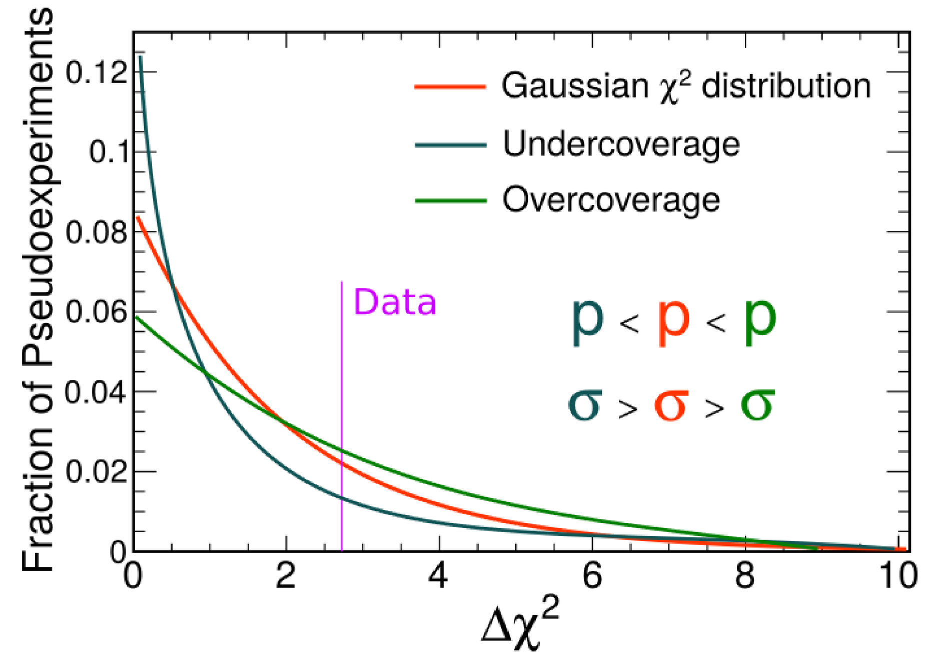
Deriving **confidence intervals** for **neutrino oscillation parameters** is statistically challenging.

Wilks' theorem [2] states that the distribution of a test statistic $\Delta\chi^2$ converges to a **standard analytical χ^2 distribution** if two conditions are met:

- **Large statistics**
- Parameters are far from **physical boundaries**

But, in **long-baseline neutrino oscillation experiments** like NOvA:

- Small interaction cross section → **low event statistics**
- Physical **boundaries**: $\sin^2\theta_{23}$ max. mixing, δ_{CP} is cyclical



$\Delta\chi^2$ distributions can deviate from a standard χ^2 distribution under certain conditions

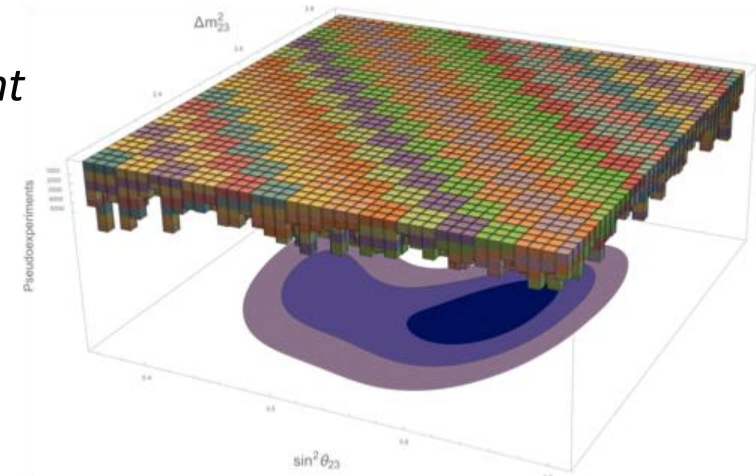
Implementation on Supercomputers

The **generation and fitting** of millions of pseudoexperiments is an ideal problem for massive **parallel computing.**

NOvA's Feldman-Cousins framework can be containerized and ported **to High Performance Computing** platforms [4].

Improvements were developed to fully leverage NERSC's computing power, like advanced **domain decomposition using Message Passing Interface (MPI)**:

DIY block-parallel environment and tools [5] are used to efficiently distribute the workload across 10^5 parallel processes.



Ongoing and future **improvements**:

- Use **Eigen libraries** instead of ROOT for linear algebra operations.
- **Multithreaded fits** to optimize memory usage.
- MPI rank communication and **dynamic load distribution** to optimize CPU efficiency and save resources.
- Replace Minuit2 with **faster** and more stable **fitter**.

Each improvement requires extensive **validation.**

Confidence interval estimation in NOvA's latest **joint neutrino-antineutrino analysis** [6] would take **several months** using standard computing resources.

This framework reduces the time to result to just **a few days** and enables previously computationally prohibitive **analysis techniques** to be explored.

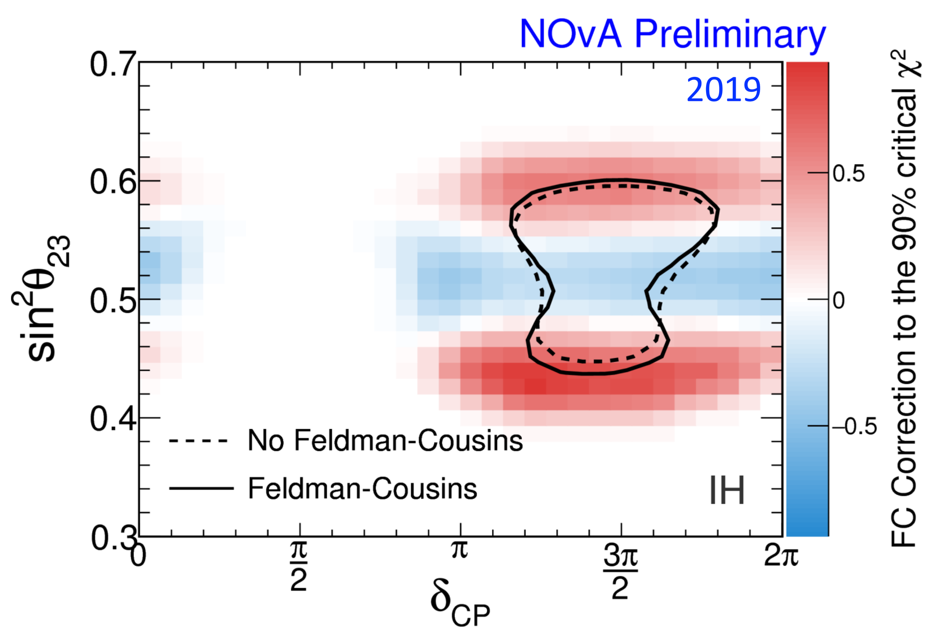
See more analysis details in Posters 83 and 354

Impact on NOvA Oscillation Results

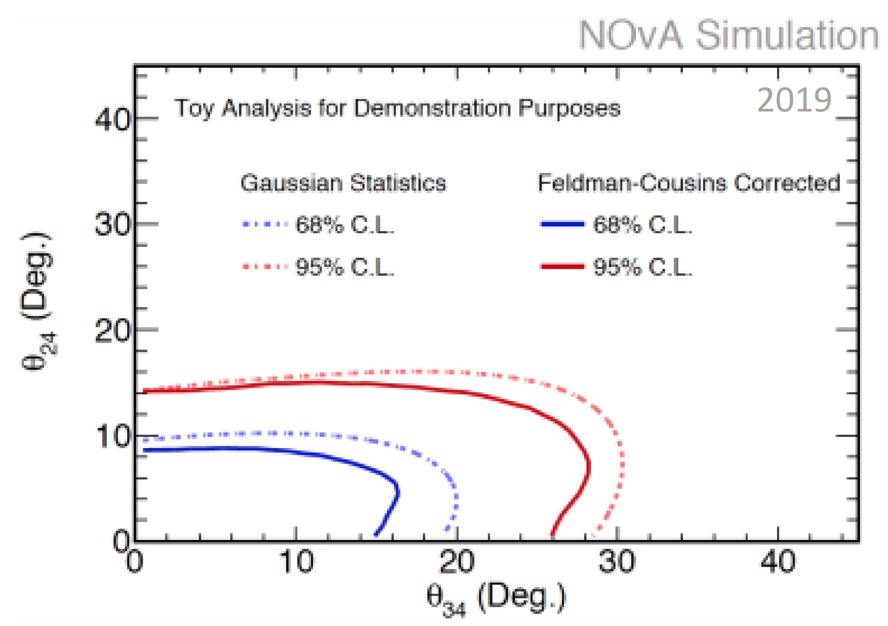
The **Feldman-Cousins unified approach** is a computationally expensive Frequentist approach to determine **statistically accurate confidence intervals** for parameters of interest.

Empirically built $\Delta\chi^2$ distributions can be skewed to the left or to the right of the standard distribution, therefore respectively **increasing or decreasing NOvA's physics sensitivities** compared to Gaussian assumptions.

See New Oscillation Results from the NOvA Experiment, A. Himmel, July 2nd



In the $\sin^2\vartheta_{23}$ vs. δ_{CP} contour above (NH), blue regions represent a sensitivity increase while red regions represent a decrease of the sensitivity.



In the ϑ_{24} vs. ϑ_{34} example contour, a correct confidence interval estimation improves the constraint on 3+1 neutrino flavor model.

References

[1] Ayres, D. et al. (2007) doi:10.2172/935497
[2] Wilks, S. (1938) doi:10.1214/aoms/1177732360
[3] G. Feldman, R. Cousins. doi:10.1103/PhysRevD.57.3873
[4] A. Sousa et al. CHEP 2018 Proceedings
[5] T. Peterka et al., LDAV'11 Proceedings (2011)
[6] M.A. Acero et al. (2019) doi:10.1103/PhysRevLett.123.151803

novaexperiment.fnal.gov
computing.fnal.gov/hep-on-hpc

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research, Scientific Discovery through Advanced Computing (SciDAC) program.