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

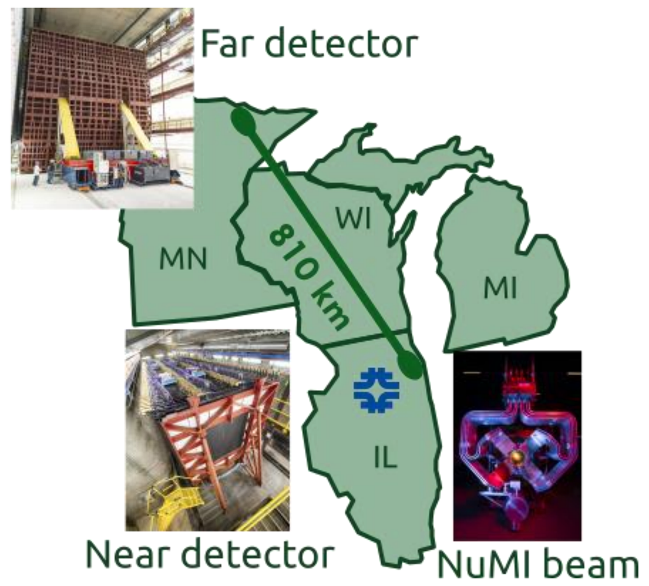
[1]Colorado State University, [2]University of Cincinnati

FERMILAB-POSTER-20-063-ND-V

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 $\vec{\theta}$

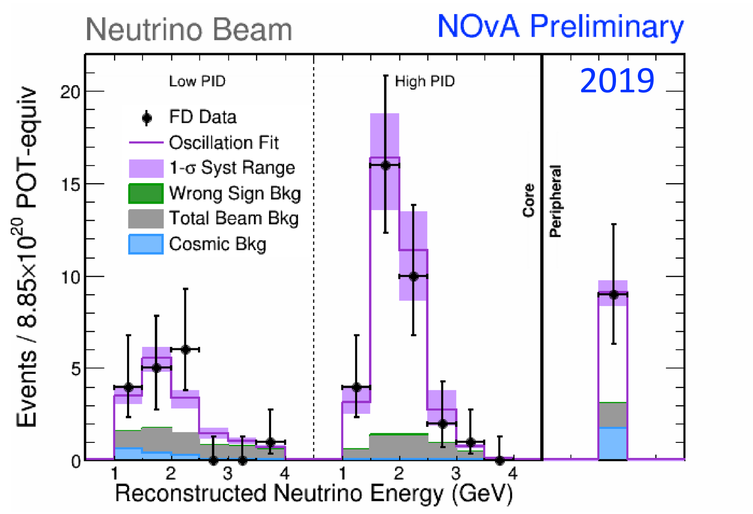
Compute a ***p*-value** analytically (Wilks' theorem) and derive a **significance**

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

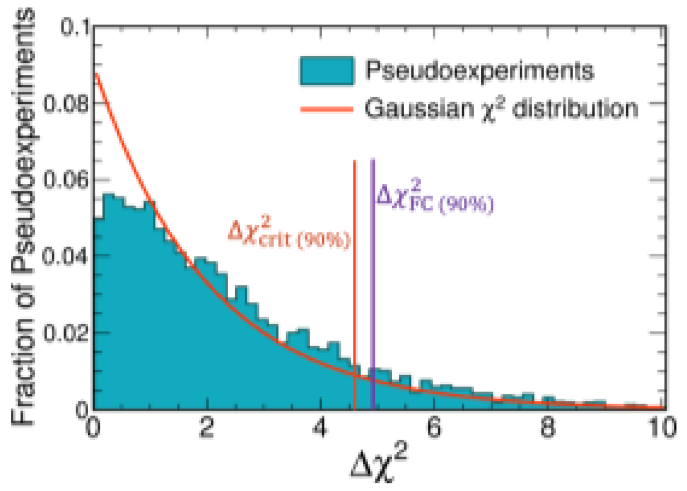
Generate and fit thousands of **pseudoexperiments** to **empirically build** a $\Delta\chi^2$ distribution for each point of the parameter space

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

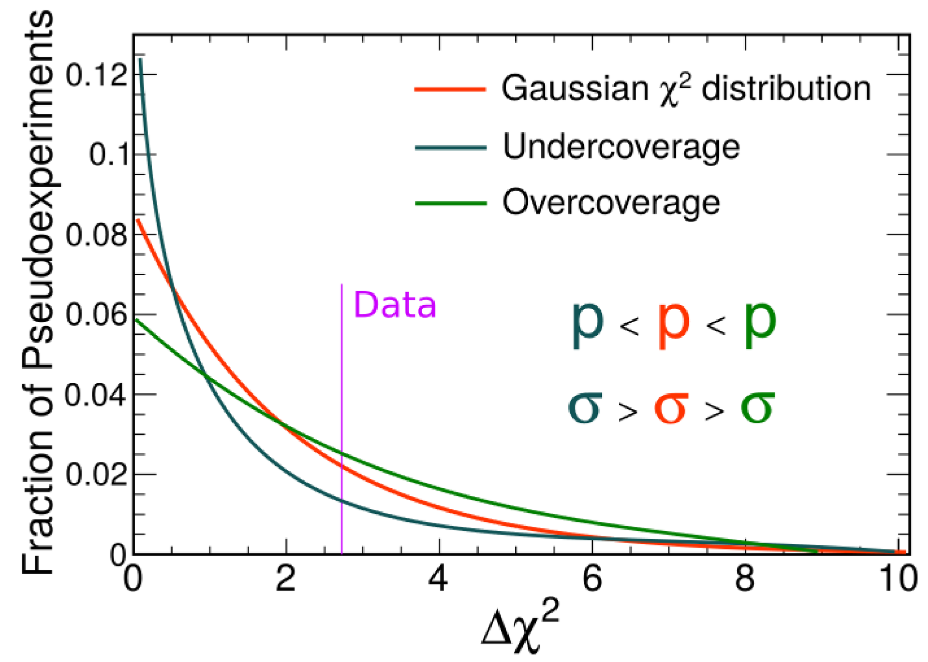
Deriving **confidence intervals** for **neutrino oscillation parameters** is statistically challenging.

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

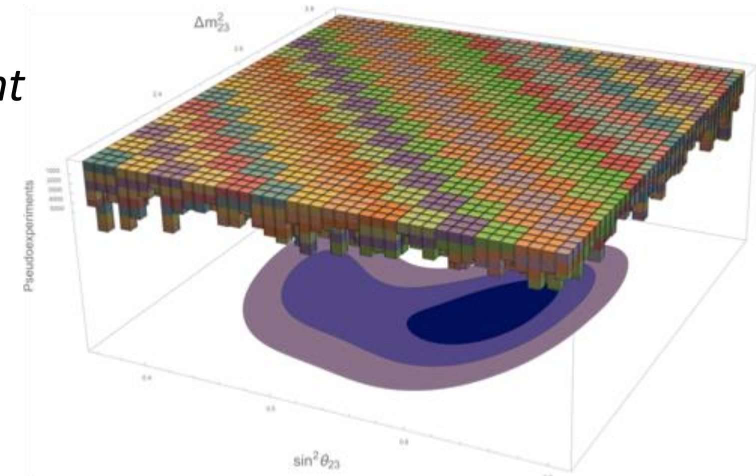
Implementation on Supercomputers

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.

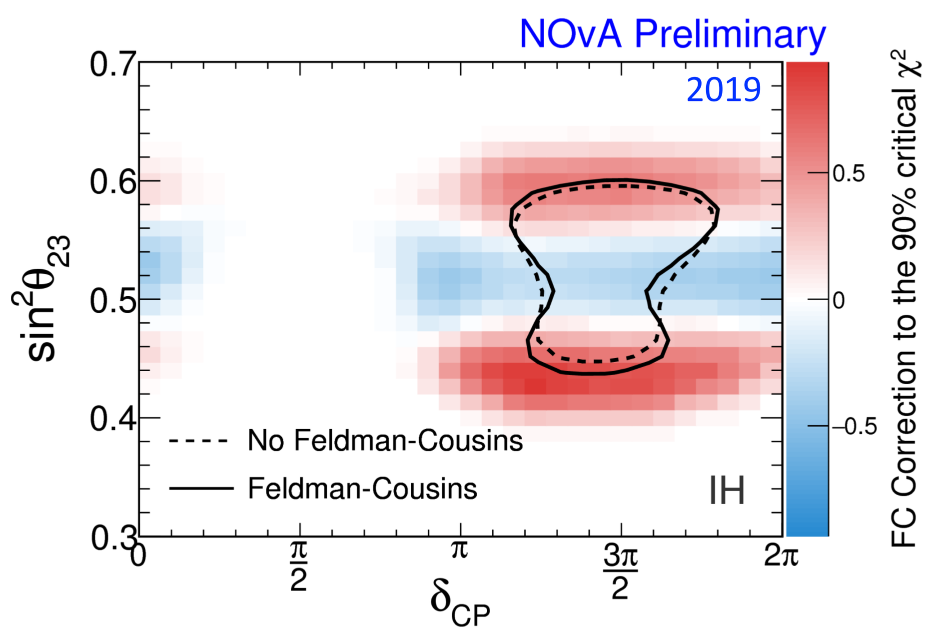
See more analysis details in Posters 83 and 354

Impact on NOvA Oscillation Results

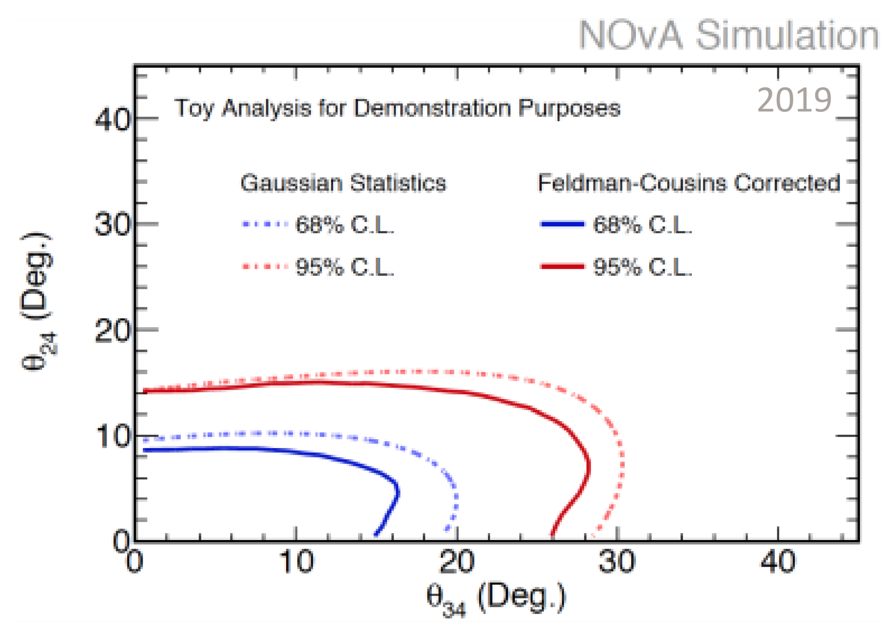
The **Feldman-Cousins unified approach** is a computationally expensive Frequentist approach to determine **statistically accurate confidence intervals** for parameters of interest.

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.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.