### Enabling Neutrino & Antineutrino Appearance Observation Measurements with HPC Facilities

#### NOvA Experiment & Neutrino Oscillation Physics

NOvA is an accelerator-based long-baseline neutrino oscillation experiment designed to measure both $\theta_{23}$ appearance and $\Delta m^2_{31}$ disappearance in order to determine the neutrino mass hierarchy and improve knowledge of the neutrino mixing structure, and probe the CP-violating phase $\delta_{CP}$.[1]

The NOvA experiment uses a modular design where both NOvA detectors use a functionally identical design and differ only in their size and locations.

The experiment features:
- A 300 ton near detector located underground, approximately 1 km from the neutrino beam production target, positioned 14 m off the beam axis.
- A massive 14 kT far detector located in Ash River, Minnesota, 812 km and 14 m off axis from the primary target station.
- The detectors sample the 703 kW NOvA neutrino beam generated at Fermilab using 120 GeV protons.

#### Multi-Universes & Feldman-Cousins

- Why do we need statistical corrections?
  - Normality: we can use a $\gamma^2$ distribution to draw confidence intervals using Wulf's theorem for statistical ensembles of measurements.
  - Neutrino oscillation measurements violate several assumptions of Wulf's theorem (low statistics, correlated parameters).

- What is Feldman-Cousins?[4]
  - A non-parametric Monte Carlo method for drawing confidence intervals under non-Gaussian situations.
  - "Pseudosamples" are generated and fitted to build up densities of distributions that replace the standard $\gamma^2$.
  - This is done at every point in the physics model's parameter space.

- The Feldman-Cousins procedure can both increase and decrease a given measurement's sensitivity to different parts of the physics parameter space.

- Example from NOvA: Comparison of $\gamma^2$ distribution and NOvA pseudo-experiments using $\Delta m^2_{31}$ in both $\theta_{23}$, $\nu_e$ and $\bar{\nu}_e$, and $\theta_{13}$, $\nu_e$ and $\bar{\nu}_e$.

#### Neutrino Oscillation Measurements

- Neutrinos have been observed to change, or oscillate, between their quantum mechanical states of lepton flavor.
- The process through which this occurs is described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing formalism and the associated mixing matrix $U$.
- Neutrino oscillations have strong constraints on the mass hierarchy and mixing parameters.

- Complicated fits to the data are required to extract the physics content.

#### Neutrino Fully-Corrected Analysis Results

- Neutrino oscillation measurements yield oscillation parameters through the combination of pseudo-experiments and fits, which makes this procedure extremely computationally intensive.

#### The Role of High-Performance Computing

- Feldman-Cousins fits/corrections can only be performed after all other stages of the analysis.
- This is because the Feldman-Cousins procedure can both increase and decrease the sensitivity to different parts of the physics parameter space.

- The future of computing focuses on leveraging the HPC centers. However, current HPC data and analysis workflows are not designed to run optimally in a massive parallel environment.

- Through the SciDAC-4 HEP Data Analysis project on NOvA, we have modified both the event selection and analysis workflows to take full advantage of HPC systems and modern libraries with implicit parallelism. Our new data/analytics model reveals that using the HEP standards, commodity hardware, and a HDS[6] table representation of the data, in this HDF5 model, we have:
  - Minimized reading, manipulation, and synchronization between processes.
  - Implemented a user-written code that looks just like serial code.
  - All data processed for a given "slice" is a single MPI rank.
  - Enabled organizing the data into a single HDF file, containing many different tables, each read by a single processor, and each optimized for its particular use case.

#### Advanced Domain Decomposition with MPI

- Have transitioned decomposition of Feldman-Cousins scan and fitting domains to use the MPI-block parallelization and tools.[3]
- Allows for automated mapping of OOF blocks into MPI ranks for maximum parallelism in HPC setting.
- Internal to each block we have begun development of multi-threaded fitting framework to minimize memory footprint and use memory of cores/threads on KNL platforms.
- Requires moving away from ROOT framework to develop a new domain-specific, multi-threaded, parallelized optimization C++ fitting libraries. This will enable us to take full advantage of vectorization hardware and KNL platforms.

#### The Future of the HEP Neutrino Analysis

- The tools being developed in collaboration with NOvA and the SciDAC-4 HEP Project are designed to enable a new paradigm for neutrino analysis that is focused on current HPC facilities and targeted for future exascale systems.

- This new model enables ALL stages of the neutrino analysis to occur within the HPC environment, and enables for the first time the capability to perform the "bare" analyses and see the impact of changes on the final physics sensitivities.

- This model leverages our HDF5 neutrino data format to combine machine learning, massive parallel event selection, advanced fitting, and automated domain decomposition to optimize and shrink the time to physics result.

- Full utilization of the next generation of HPC platforms will enable physicists to probe to greater extent and at higher sensitivity to the most important questions of the neutrino world.

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References:
[3] A. Cousins fits/corrections can only be performed after all other stages of the analysis.

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####变更数据和模型分析

- 通过分析，我们发现当前的HEP数据和分析工作流程并不适合在大规模并行环境运行。
- 通过SciDAC-4 HEP数据分析项目在NOvA上所做的工作，我们已经修改了事件选择和分析流程，使其能够充分利用HPC系统及现代库中的隐式并行性。我们的新数据/分析模型揭示，使用HEP标准、商用硬件和HDF5[6]表格表示的数据，在这种模型中，我们实现了：
  - 最小化读取、操作和进程间同步。
  - 实现了一种完全可移植的代码。
  - 所有数据处理都是在单个MPI进程中完成的。
  - 提供了一种开放的、可扩展的解决方案。

####高性能计算

- 高性能计算的重点是利用HPC中心。然而，当前的HEP数据和分析流程并不设计为在大规模并行环境中运行。

####未来

- 未来将发展在与NOvA合作的基础上，SciDAC-4 HEP项目正在开发一种全新的中微子分析框架，该框架重点关注当前的HPC基础设施，并为未来的超算系统所用。

- 这个新模型的开发使未来中微子分析能够运行于HPC环境内，为未来中微子分析提供了一个全新的舞台，以应对复杂的物理挑战。

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####示例表

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