FERMILAB-POSTER-24-0082-V

Determination of neutrino oscillation parameters through the Feldman-Cousins method by the NOvA Experiment

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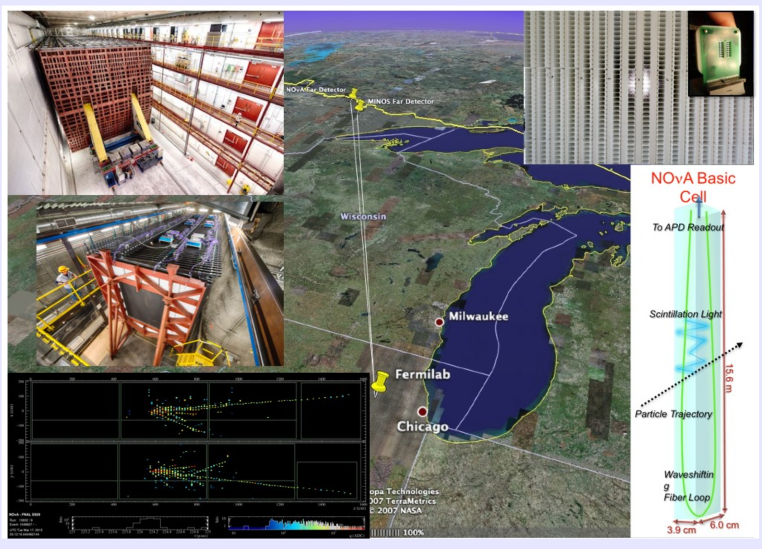
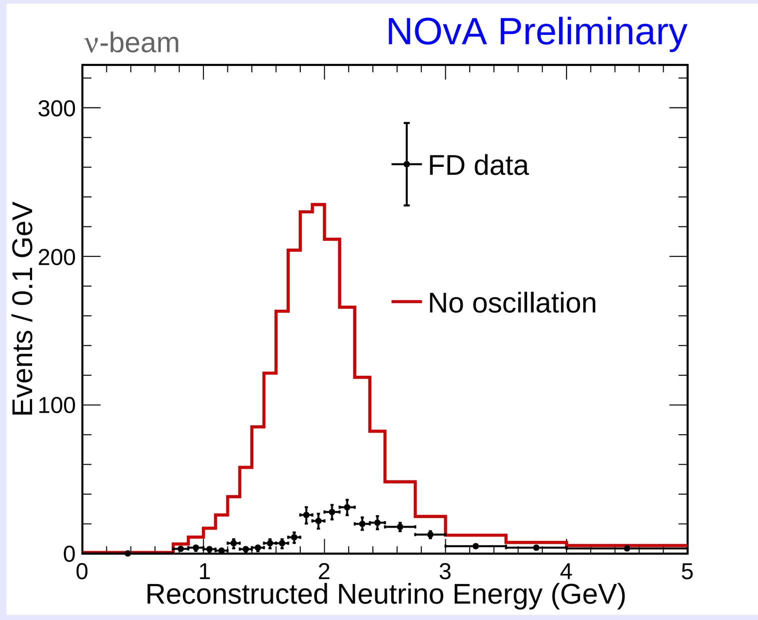
The NOvA Experiment

- Long-baseline accelerator experiment
- 810 km from Near (ND) to Far Detector (FD)
- 2 GeV Peak
  - off-axis narrow-band ν ($\overline{\nu}$) beam
- World's most powerful $\nu_\mu(\bar{\nu}_\mu)$ beam at 700+ kW
- 10 years of data
  - 26.6×10^{20} POT-equiv. ν-beam
  - 12.5×10^{20} POT $\overline{\nu}$-beam



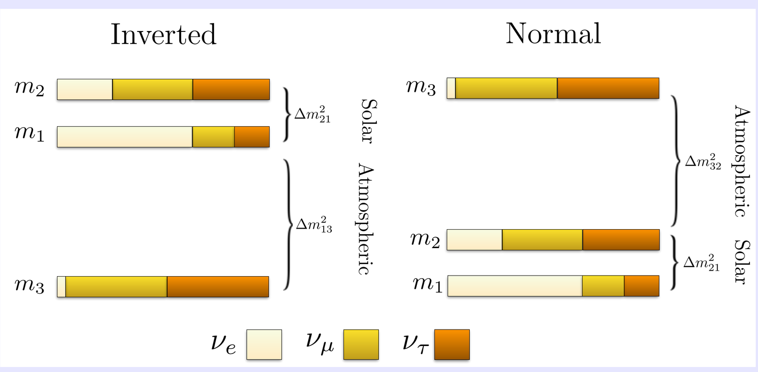


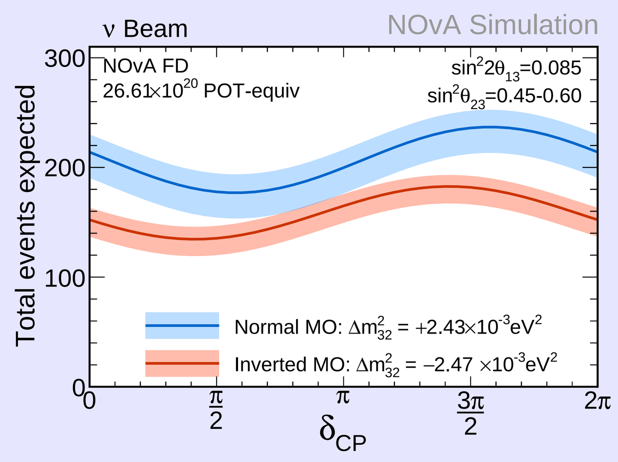
NOvA Oscillation Capabilities

Probability of oscillation dependent upon the PMNS parameters, baseline, and neutrino energy

$$P_{\nu_\mu \to \nu_e} \approx 4\cos^2(\theta_{13})\sin^2(\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\frac{\Delta m^2_{32} L}{E}\right) + \ldots \quad (1)$$

- Some open questions remains:





NOvA observes $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$, sensitive to θ_{23}, δ_{CP}, and sgn (Δm^2_{32})

Frequentist Interpretation of Oscillation Data

This analysis fixes θ_{12} and Δm^2_{21} [1], and apply a reactor constraint to θ_{13} [2]. θ_{23}, δ_{CP}, and Δm^2_{32} are freely fit, for each mass ordering separately. 68 systematic uncertainties are applied as gaussian penalty terms during the fit.

The Profiled Feldman-Cousins Method

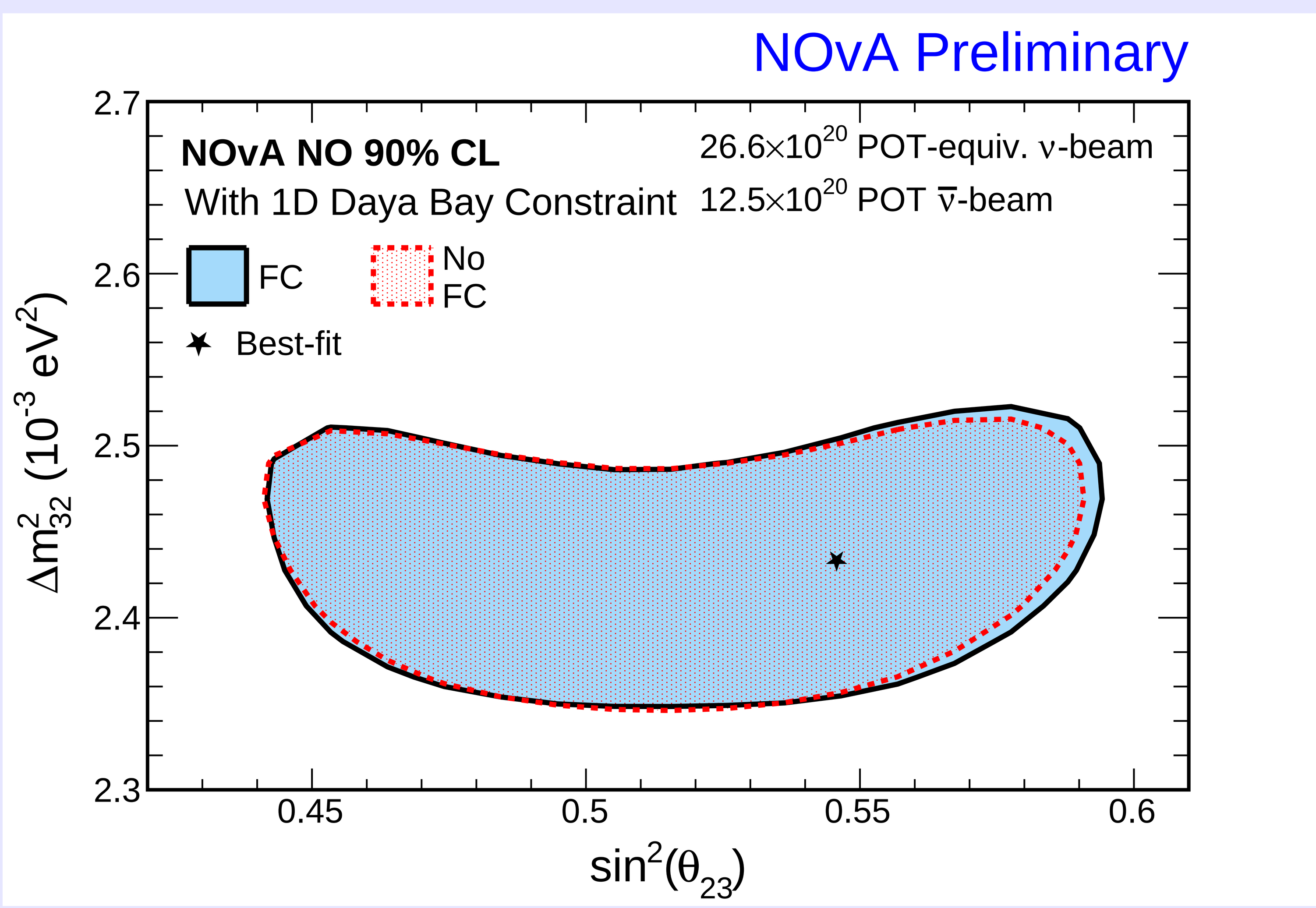
- Assumption that likelihood follow a χ^2 distribution relies on Wilks' Theorem
- NOvA data does not entirely satisfy, hence extra steps to construct confidence intervals are needed [3]

Feldman-Cousins method generates empirical distributions for the log-likelihood test statistic

- Generate many pseudo-experiments (PSEs) for each combination of fit variable, while fixing (profiling) over all non-fit (nuisance) parameters
- Calculate $\Delta\chi^2$ between the PSE and best fit to data
- Sort list of $\Delta\chi^2$ values and calculate critical point based on confidence level

Computational Methods for Feldman-Cousins

- FC is computationally expensive, requiring 10's of thousands of PSEs per bin
- Parallelism is leveraged with MPICH and the DIY package for C++, and utilization of NERSC's Perlmutter supercomputer



Results

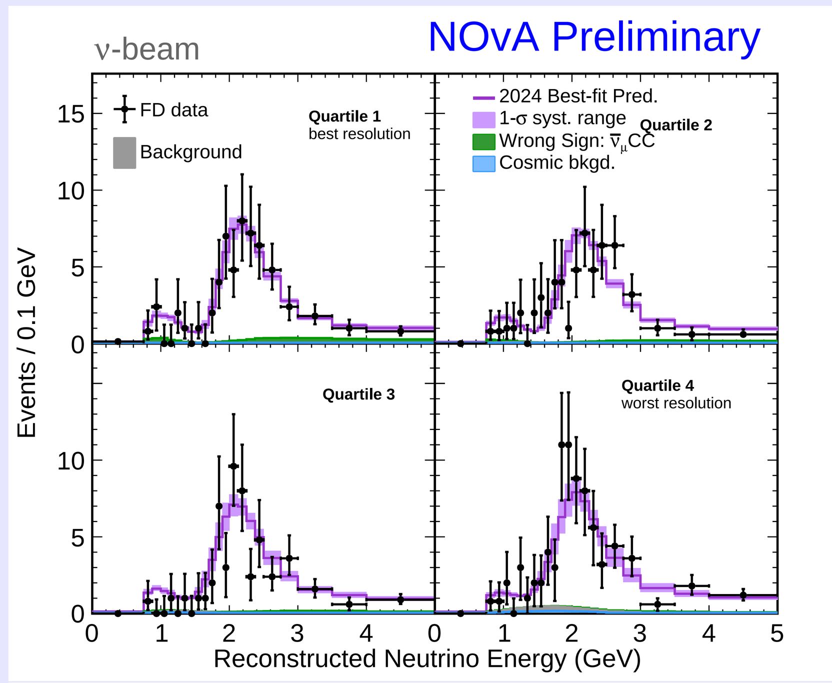
NOvA presents the results of a frequentist analysis of 10 years of FD oscillation data:

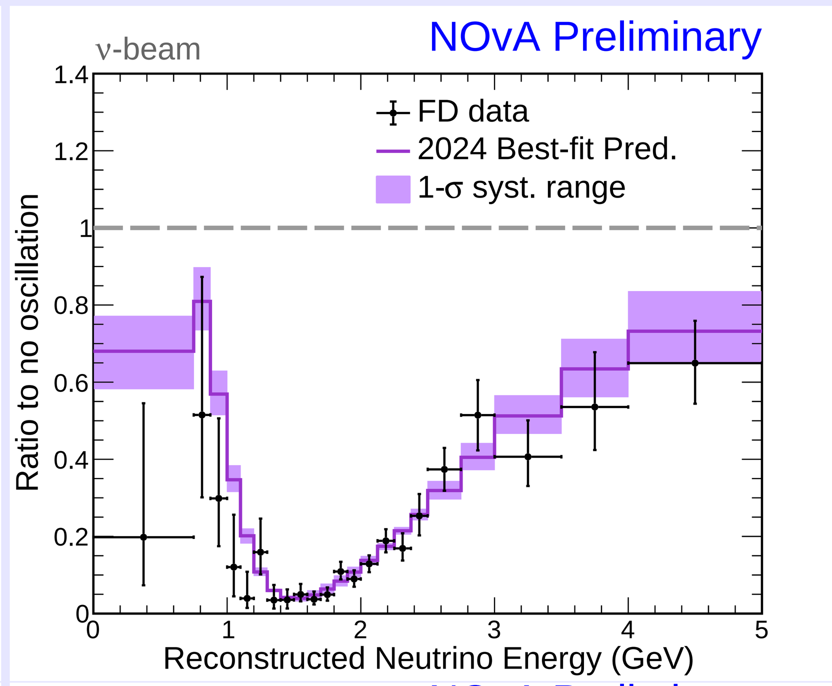
- Joint $\nu_\mu(\bar{\nu}_\mu) + \nu_e(\bar{\nu}_e)$ fit, including a novel low-energy ν_e sample

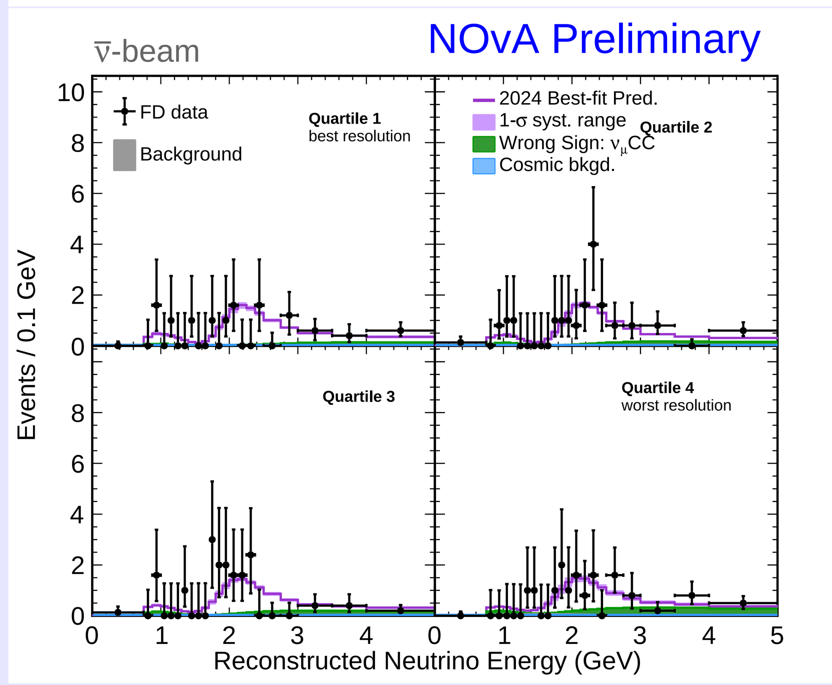
10 years of NOvA Data	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	Low-E ν_e
FD Observed Events	384	106	169	32	12
Background	11.4	1.7	55.0	12.3	6.8

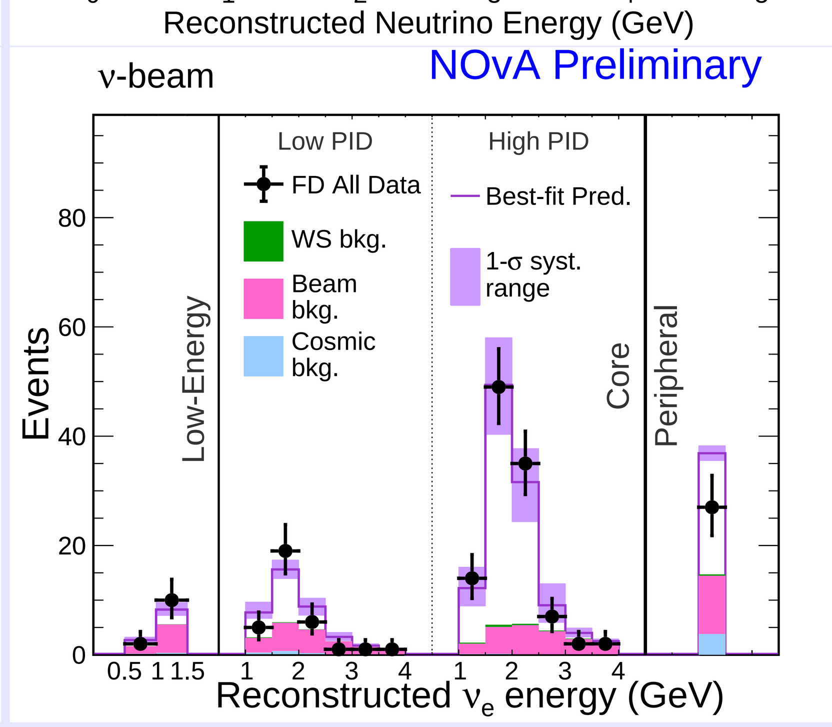
Best-Fit Values

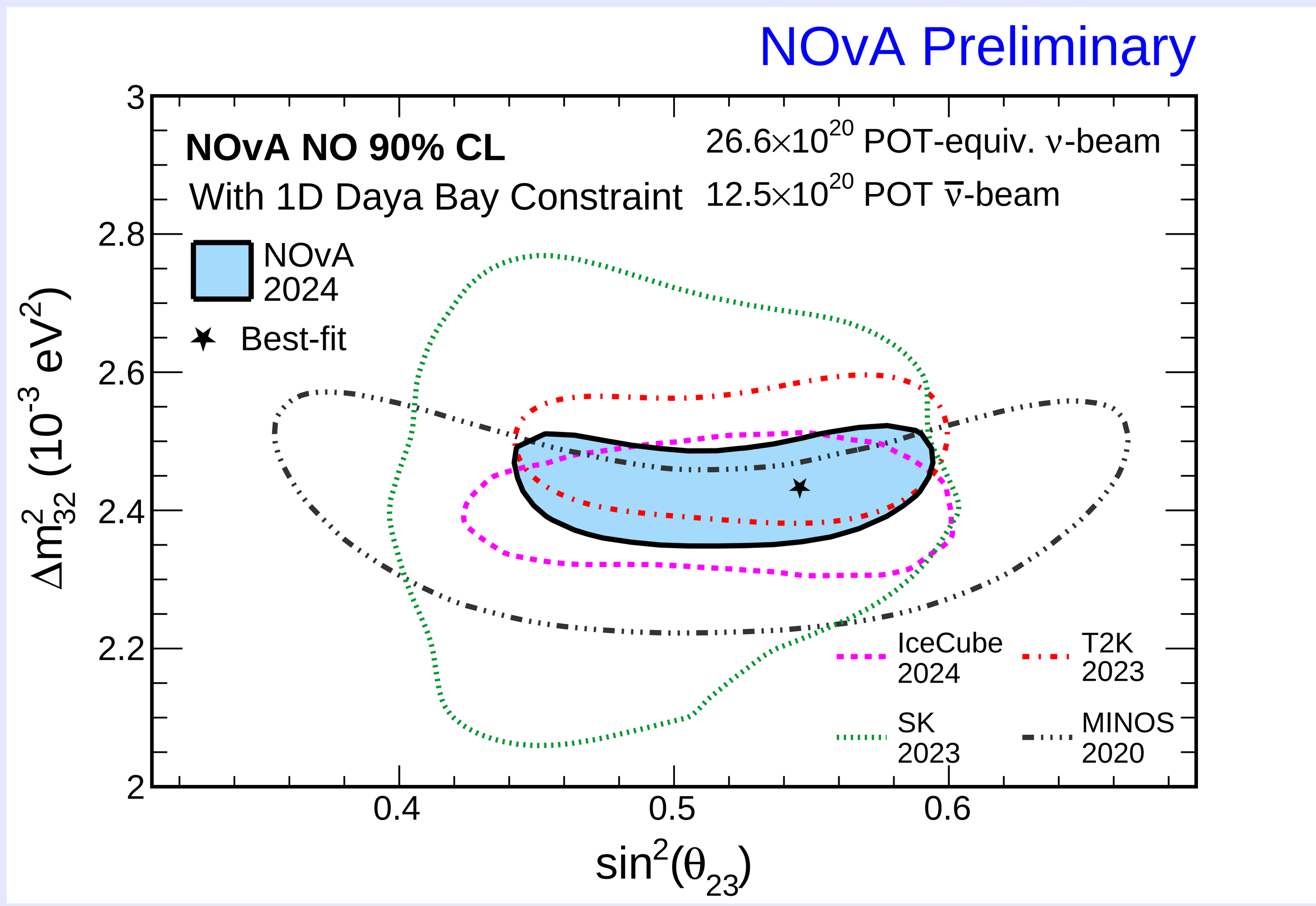
Parameter	Best-fit	Normal Ordering Preference (σ)	
$\sin^2(\theta_{23})$	$0.546^{+0.032}_{-0.075}$	W/ 1D Daya Bay	1.36σ
Δm^2_{32} $(10^{-3}\,\mathrm{eV}^2)$	$2.433^{+0.035}_{-0.036}$		
δ_{CP} (π)	0.875	W/ 2D Daya Bay	1.57σ



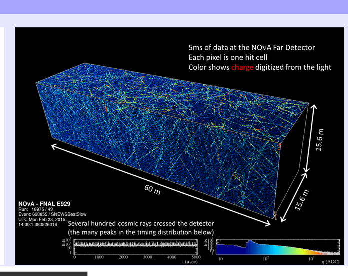








View the NOvA Live Event Display!



@novaexperiment

See also Poster #450

Ben Jargowsky and Liudmila Kolupaeva

"Bayesian Fit for the NOvA Three Flavor Oscillation Analysis"

Acknowledgements

This document was prepared by the NOvA Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

References

[1] Workman, R. L. & Others. Review of Particle Physics. *PTEP* **2022**, 083C01 (2022).

[2] An, F. P. *et al.* Precision measurement of reactor antineutrino oscillation at kilometer-scale baselines by daya bay. *Phys. Rev. Lett.* **130**, 161802 (2023).

[3] Acero, M. A. *et al.* The profiled feldman-cousins technique for confidence interval construction in the presence of nuisance parameters (2022). 2207.14353.