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jaxnu-osc: A Fully Differentiable Neutrino Oscillation Engine with Applications in Experimental Sensitivity Optimization

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Next-generation neutrino oscillation experiments operate in highly complex parameter spaces where the physics of interest is tightly coupled with multi-dimensional systematic uncertainties. Traditional neutrino oscillation calculators lack gradient information, limiting experimental design, sensitivity forecasting, and profile likelihood fits to computationally expensive, derivative-free grid scans. To address this bottleneck, we present jaxnu-osc, a high-performance, open-source Python package providing a complete, fully differentiable neutrino oscillation engine. The software calculates exact 3-flavor neutrino propagation through continuously varying matter profiles while natively providing exact analytical gradients with respect to all physical, atmospheric, and environmental parameters.

In this work, we demonstrate the unique capabilities of a gradient-aware framework through a primary, physics-driven use case: automated experimental sensitivity optimization. Utilizing a continuous soft-binning architecture, we show how jaxnu-osc calculates exact sensitivity gradients to dynamically warp and optimize 2D analysis bin boundaries (Energy vs. Zenith Angle), mathematically maximizing an experiment's statistical sensitivity to neutrino oscillations. Additionally, we showcase how this differentiable pipeline seamlessly accelerates high-dimensional parameter profiling, such as simultaneous fits of complex Non-Standard Interaction (NSI) matrices or Earth core characteristics. We present the package validation, performance benchmarks, and discuss how jaxnu-osc can be integrated into existing experimental simulation workflows to automate and enhance analysis design.

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