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Group Invariance in Quantum Fidelity Kernels for Vector Boson Scattering Identification at the LHC

In the high-luminosity era of particle physics, advanced computing methods are vital for tackling the unprecedented scale and complexity of data, inspiring us to explore innovative quantum approaches for data analysis. We investigate the impact of incorporating problem-specific permutation invariance into hardware-efficient quantum fidelity kernels for high energy physics data analysis in terms of classification performance and model scalability, and to demonstrate this approach, we tackle the problem of identifying rare vector boson scattering (VBS) events from the abundant QCD multijet background by exploiting the pairwise permutation invariance of the final-state jets in the kernel design. We introduce a novel quantum kernel model, Bivariate Permutation-Invariant Fidelity Quantum Kernel (BPINVFQK), alongside partially and fully symmetrized variants of the standard hardware-efficient ansatz, which embed the S_n group invariance to reflect the underlying symmetries of the VBS process. The models are trained and evaluated using simulated samples from the CMS experiment at the CERN LHC. Under ideal, noise-free conditions, these symmetrized models yield statistically significant improvements in classification performance—demonstrated by higher mean AUC values and improved centered kernel alignment compared to both the baseline HEA model and classical RBF kernel. However, under realistic shot noise conditions (10,000 shots), the performance benefits significantly diminish, highlighting challenges for a NISQ-era implementation. This motivates investigation into testing the models with higher shot counts to recover and further enhance the observed performance under shot noise. Additionally, our hyperparameter analysis reveals a critical dependency on the kernel bandwidth γ: smaller γ values promote anti-concentration up to a threshold, after which all models begin to concentrate, while BPINVFQK exhibits hints of sub-exponential scaling at higher bandwidths, indicating a promising scaling capability. Finally, experimental results gathered from VTT's Q50 quantum computer corroborate our simulation findings, underlining the practical challenges and opportunities in deploying symmetry-enhanced quantum kernels on contemporary quantum hardware.

Secondary track

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