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Quantum-Enhanced Inference for Four-Top-Quark Signal Classification at the LHC Using Graph Neural Networks

Rare event classification in high-energy physics (HEP) plays a crucial role in probing physics beyond the Standard Model (BSM). Such processes serve as indirect searches for new physics by testing deviations from SM predictions in extreme kinematic regimes. The production of four top quarks in association with a (W^-) boson at $(\sqrt{s} = 13)\ TeV$ is an exceptionally rare SM process with a next-to-leading-order (NLO) cross-section of $(6.6^{+2.4}_{-2.6} ab)$. In its fully hadronic decay mode, with intricate jet topology and overwhelming QCD background, demands advanced techniques for signal extraction, making it a prime candidate for new physics probes like anomalous top-quark interactions or EFT deviations . Identifying this process in the fully hadronic decay channel is particularly challenging due to overwhelming backgrounds from $t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, and triple-top production processes. This study introduces **CrossQuantumPhysGNN (CQPGNN)**, a quantum-classical hybrid graph neural network (GNN) designed to tackle rare event classification. CQPGNN integrates GINEConv layers for particle-level features, a quantum circuit employing angle encoding and entanglement for global feature processing, and cross-attention fusion to combine local and quantum-enhanced global representations. Physics-informed losses enforce momentum conservation and jet multiplicity constraints derived from the event decay dynamics, making a faster physics informed convergence. Benchmarked against conventional methods, CQPGNN achieves a signal significance $(S/\sqrt{S+B})$ of $0.174 \pm 0.05\%$, recall of 0.957, and ROC-AUC of 0.961, surpassing BDTs $(0.148 \pm 0.04\%, 0.914, 0.908)$ and Xgboost $(0.149 \pm 0.04\%, 0.924, 0.913)$. The classification models are trained on parametrized Monte Carlo (MC) simulations of the CMS detector, with events normalized using cross-section-based reweighting to reflect their expected contributions in a dataset corresponding to $350 fb^{-1}$ of integrated luminosity. This ensures that significance calculations accurately reflect realistic collider conditions. The proposed method is benchmarked against conventional machine learning approaches, with results demonstrating improved classification significance. This quantum enhanced approach offers a novel framework for precision event selection at the LHC, leveraging high dimensional statistical learning and quantum-enhanced inference to tackle fundamental HEP challenges, aligning with cutting-edge ML developments.

Field

Pheno

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