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A general approach to quantum integration of cross sections in high-energy physics

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Monte Carlo integration lies at the heart of theoretical predictions in high-energy physics (HEP), underpinning the simulation of scattering processes at facilities like the Large Hadron Collider. However, as the complexity of target processes grows, classical methods rapidly become computationally demanding, consuming billions of CPU hours annually. In this talk, I will present a general-purpose framework for quantum-enhanced integration of cross sections in HEP, focusing on universal "building blocks"that are based on Fourier Quantum Monte Carlo Integration. Leveraging Quantinuum's Quantum Monte Carlo Integration engine, this approach offers an efficient, extendable methodology for generating quantum circuits that calculate these integrals, with a quadratic improvement in root mean-squared error convergence compared to classical Monte Carlo methods.

I will outline how complex, multi-dimensional cross-section integrands can be decomposed into separable products of fundamental components—monomial functions and relativistic Breit-Wigner distributions—that can themselves be naturally mapped to efficient quantum circuits. Special attention will be given to state-preparation strategies for encoding the relativistic Breit-Wigner distributions on quantum hardware, comparing two different techniques, and analysing their trade-offs in terms of scalability, circuit depth, and preparation fidelity.

To illustrate the practicality of this framework, I will walk through a concrete example: the $1 \longrightarrow 3$ decay process of the tau lepton into three fermions (at tree level). Through this case study, I will show how the framework effectively incorporates experimental selection criteria through quantum thresholding operations, and achieves integral estimations with tunable precision. Additionally, I will present performance benchmarks, including resource assessments for this example for both near-term (NISQ) devices and future fault-tolerant quantum architectures.

Beyond this example, I will discuss the pathway toward scaling to more complex processes, such as multi-boson production or higher-order corrections in perturbative QCD, and outline how these quantum-enhanced techniques could reshape the computational landscape of HEP. This work represents a significant step toward practical quantum advantage in scientific computing, offering a vision for how quantum processors may help augment classical HPC infrastructure in future HEP analysis pipelines.

Secondary track

Authors: WILLIAMS, Ifan (Quantinuum); PELLEN, Mathieu (University of Freiburg)

Presenter: WILLIAMS, Ifan (Quantinuum)

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