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Quantum tomography at the energy frontier

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Abstract: Quantum mechanics is undergoing a theoretical and experimental renaissance. Quantum tomography is a method to reconstruct everything describing a quantum system by observing lower dimensional projections of its density matrix. Applications analyzing Drell-Yan production in proton-proton collisions and dijet photoproduction have been recently conducted. These studies are among the first to find evidence of quantum entanglement at the energy scale of the LHC. Applications of quantum tomography have the potential to find new model-independent structures in the data in a wide variety of processes, and uncover correlations that cannot be expressed in the language of classical distributions. Quantum tomography can also be used to design experiments aiming at testing foundation postulates of quantum mechanics.

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With the advent of the High-Luminosity Large Hadron Collider (HL-LHC), experimental physicists are preparing for new studies with the aim of understanding physics phenomena within and beyond the realms of the standard model of particle physics. Thanks to improved detectors, the increasingly larger size of datasets, and the lessons learned from Run 1 and Run 2 experiments, as well as developments from the theoretical side, the expectations of the community for high-profile findings at the LHC are high. At the same time, the community is aware that new approaches to analyze the data are needed. For these reasons, the community has recently engaged in conversations and projects utilizing machine learning, deep learning and artificial intelligence.

Quantum tomography (QT) is a model-independent method to experimentally measure system density matrices with experimental data. The process systematically builds higher dimensional structures from lower dimensional projections. QT is inherently model-independent, does not need perturbative theory assumptions, and bypasses volumes of unobservable field-theoretical superstructure. We have prepared real-word experimental applications of QT and entanglement for collider physics for the first time[1], exploiting concepts of reduced density matrices and the symmetries of the underlying probes.

Quantum probability (QP) is the primary discovery of quantum mechanics, which constructs an exponentially-efficient extension of the framework of classical probability. Many features of QP cannot be described by classical distributions, which leads to a perception of paradoxes. It is not possible to add those features onto classical simulations consistently. Quantum tomography explicitly builds in quantum probability, including the Born rule and projective rules of quantum mechanics. That leads to quantum theoretically–informed features of artificial intelligence that go far beyond the existing technology of sampling distributions on high-dimensional spaces. When QT is applied to experimental data, features emerge which cannot in principle be described in the language of classical correlations and distributions, due to entanglement. And the signals of entanglement in particle physics data are not delicate table-top experimental stunts, but "relative order one" effects no classical model can accommodate.

Subsequent to the introduction of quantum tomography in collider physics[1], several applications have recently been presented at the APS Division of Particle and Fields meeting[2] and at the 2020 ICHEP conference[3]. Quantum entanglement is found in Drell-Yan data in pp collisions, as well as a resonance-like spin-vortex structure that has no precedent in the literature. Applications to dijet photoproduction have also found quantum statistical structures underlying the classical distributions of experimental work. There is no possibility to describe either system as *separable*, namely not entangled.

A new way to think with quantum mechanics is needed to exploit its long-awaited renaissance. In a modern approach[4] everything is practical, comprehensible, and computable. The time is right for high energy physics to benefit from the reconstruction of quantum mechanics in recent years.

Applications of quantum tomography to LHC, RHIC, and the data of future facilities such as the FCC and EIC will provide novel ways to uncover new phenomena. It can also be used to prepare experiments aiming to test foundation postulates of quantum mechanics. Currently available datasets and future data in both proton-proton and heavy-ion collisions at RHIC and LHC can be analyzed using the technique. We anticipate QT will be of great interest for the high-energy physics community in the coming years.

References

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