Quantum Computing Search and Simulation for Decays to Dark Sector Particles

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Quantum search for decays to the dark sector

The Higgs boson that was discovered at the LHC [1] [2], if it is the standard model (SM) boson, will couple to SM particles in a manner that is unlike any other lepton, quark, or gauge boson; it's coupling strength is related to the particle's mass. If the nature of its coupling depends on the mass of the state it couples to, it may provide a new means to search for phenomena that is beyond the SM of particle physics. The Higgs boson could provide portal to a so-called Dark Sector of new particles and interactions, coupling to them in a unique way that cannot be probed with other SM probes. Totally new physical states may therefore be accessible experimentally, via coupling to the Higgs boson, in a way that did not exist previously.

Theoretical studies, supported by astrophysical and cosmological experimental data, indicate that these Dark Sector particles can lead to very rare events in LHC collisions [3] [4] [5] [6]. An example LHC Dark Sector search would consist of detecting a resonance that decays to leptons. Leptons are a class of structureless particles with spin-1/2 that do not exhibit strong interactions. Leptons can be electrons e), muons (μ), tau particles (τ), or neutrinos (ν_e, ν_μ, ν_τ). In the study described here, we chose to search for a resonance that decays to electron-positron or positive muon and negative muon pairs. This resonance that signals a new particle would be seen above a broad spectrum of background SM events [7].

Electron and positron candidates consist of clusters of energy deposited in the electromagnetic calorimeter associated with their tracks inside the detectors. The clusters matched to tracks are required to satisfy a set of identification criteria that require the longitudinal and transverse shower profiles to be consistent with those expected for electromagnetic showers. These are registered as hits, that are then translated in software to electron and positron energies, momenta, charges, and position at any given time.

Positive and negative muon candidates are formed by matching reconstructed detector tracks in one spectrometer subsystem with either complete or partial tracks reconstructed in a separate spectrometer. If a complete track is present, the two independent momentum measurements are combined; The particles are identified as muons if their calorimetric energy deposits are consistent with a minimum ionising particle.

A novel quantum search of lepton transverse momenta at the ATLAS LHC detector was designed based upon these experimental procedures and information. The information described in the previous two paragraphs are converted into database entries that are appropriate for the method designed for Dark Sector searches using exotic decays of the Higgs boson, and with a format that can be understood and used by the quantum search algorithm. In this study, Grover's quantum search algorithm was used [8][9][10][11]. In the study, the proper state is identified in the algorithm, and the algorithm is then run on the IBM quantum computer. The correct state is identified more than 87% of the time. Finally in addition to the Grover search one can also explore searches for rare decays using quantum annealing [12] and quantum random walks [13].

Quantum simulation for decays to the dark sector

Quantum simulation can play two roles for decays to the dark sector. One role is in event generation for possible signals in the LHC detectors [14]. Indeed one can easily adapt the quantum event generation models to include decays through the dark sector through a fermionic or bosonic portal field which is charged under both the Stadard Model and Dark sector gauge groups. Finally in the case of SIMP (Strongly Interacting Massive Particle) scenarios for dark matter [15] one can use quantum computers to simulate and calculate expectation values for effective Hamiltonians describing decays to the dark sector similar to what is being proposed for the quantum simulation of lattice QCD. It is conceivable that these quantum simulations of strongly interacting dark matter could have an advantage over classical simulations for example if the dark sector contains a nonzero theta angle so that topological terms in the action are present. Also in the early Universe cosmology the dark sector could interact strongly with matter and gravity and a quantum simulation could also have an advantage over classical simulation [16]. This is because the Euclidean action for the gravity-matter-dark-matter system is not positive definite and like the case with nonzero theta angle is not suitable for Monte Carlo simulation.

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