Improving Efficiency of Particle Jet Clustering using Hybrid Classical-Quantum Annealing

***Authors:** Ishan Goel, Cole Murphy, Sean Wall, Gino Daniels, Bornik Nag, Ayusha Patra*
***Mentors:** Robin Carpenter, Dr. Andreas Jung*

Source code, data & references available

OVERVIEW

The CMS experiment at the LHC investigates the production of top quark pairs through the final state properties of particles measured in proton-proton collisions. Analysis requires knowledge of the origin of these particles, creating the need for efficient clustering algorithms customized for particle collisions. We explore how quantum annealing, a form of quantum computing, may be viable for reducing the computational complexity of existing clustering methods.

Background

Particle Jet Clustering

Clustering algorithms employed by CMS have access to a large amount of data collected about particle tracks resulting from a collision, including transverse momenta and positions, the two parameters that the algorithms discussed here operate with.

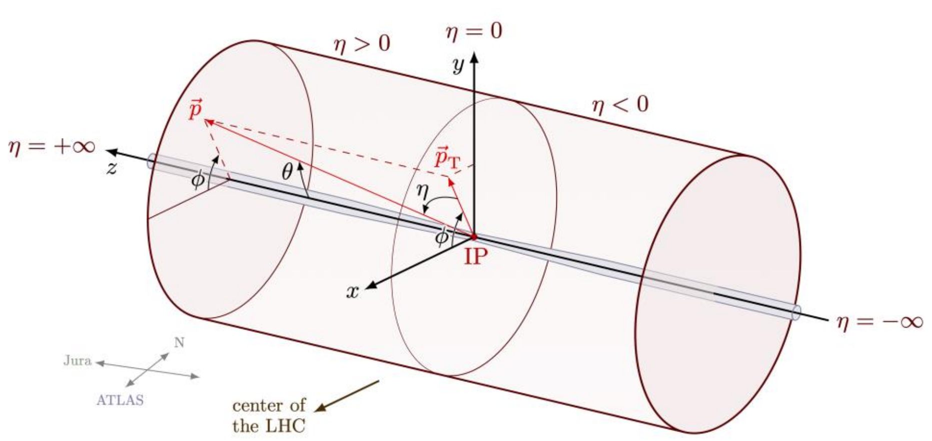

Fig 1: The CMS coordinate system

Quantum Annealing

In a quantum annealer, qubits are influenced by a programmable magnetic field to induce an energetically favorable bias towards a certain state. Qubits can be coupled to other qubits through a weight term, allowing for the creation of complex energy landscapes. Since qubits naturally evolve towards lower energy states, by setting weights and biases carefully, a problem can be encoded such that good solutions correspond to lower energies. Measuring the qubits then produces solutions.

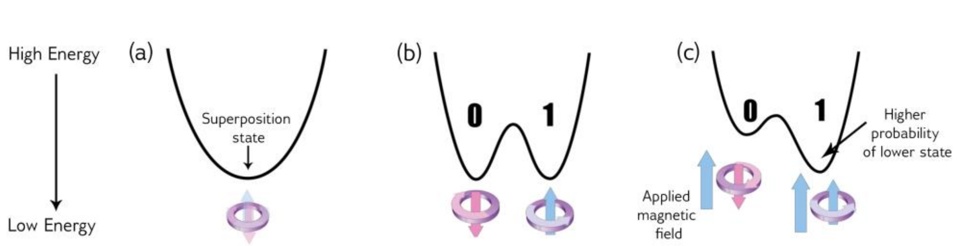

Fig 2: Effect of a magnetic field on a single qubit

Methodology

The anti-kt algorithm, which is currently used by CMS, was used as a baseline to compare QA against. Problem sets were generated with the following key features:

1. Sets for 2, 3, 4, and 5 vertices (track origins) with 20, 18, 16 and 12 tracks respectively.
2. Sets were either generated with standard deviations 0.03 or 0.05 of the normalized z and Φ coordinates (see Fig 1)
3. The momenta follow an inverse square distribution similar to those observed at CMS.

The quantum annealing method was implemented as a QUBO problem with the following key features:

1. (Hybrid part) A modified O(n) version of anti-kt was used to form a guess for the number of vertices in the problem.
2. A pair clustered together have a cost based on logarithmically-distorted pairwise distance.
3. High momentum particles are penalized from being clustered together
4. A constraint term to disallow particles from belonging in multiple clusters.

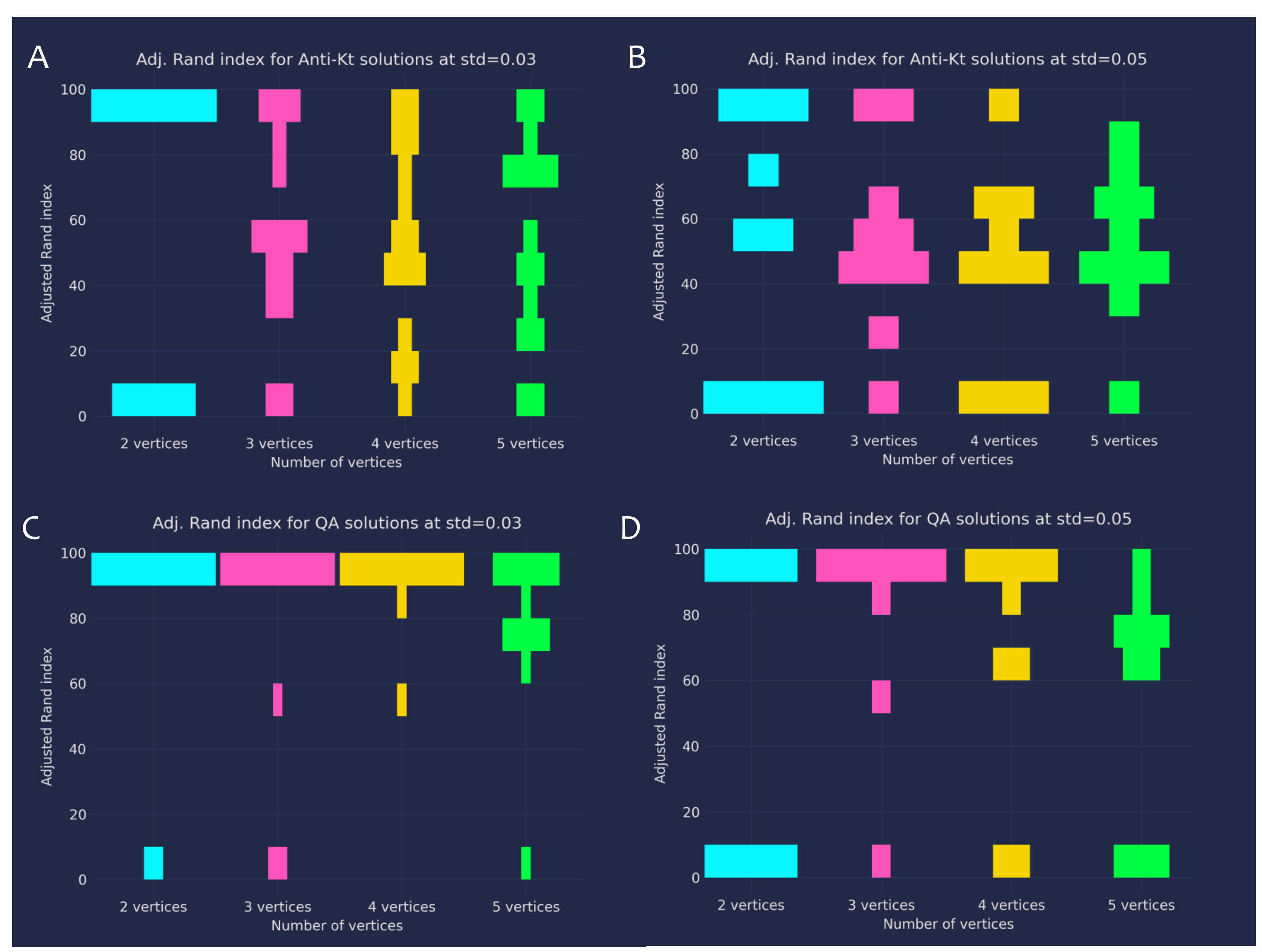

Fig 3 A-D: Accuracy of the two methods for different problem configurations

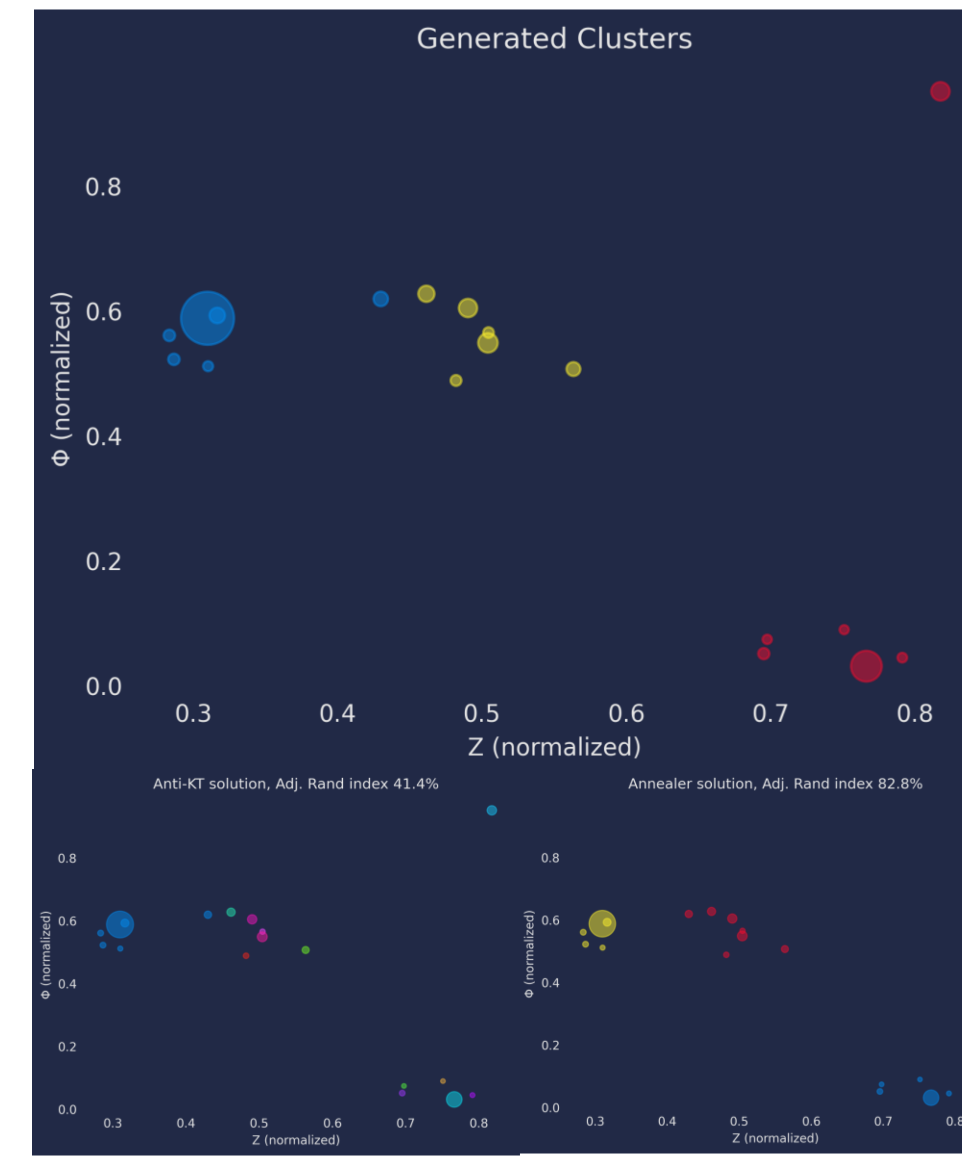

Fig 4: Example problem with 3 vertices and std 0.05

Results

It's evident that the QA method is generally better than anti-kt at clustering when the adjusted Rand index is used to score solutions. A higher Rand index indicates greater agreement with the ground truth. Generally, the QA solution is close to perfect or completely incorrect (usually because of a constraint violation), whereas anti-kt produces mostly mediocre results, as seen clearly in Figure 3. The two methods differ in their response to an increased standard deviation or increased vertices. Increasing the standard deviation or vertices with the quantum annealer results in the proportion of completely incorrect solutions increasing, whereas with anti-kt, the solutions simply drift towards being worse. QA solutions thus exhibit greater variance than anti-kt ones, and have generally better accuracy.

Conclusion

While we see very positive results from using quantum annealing, and while it may seem like CMS should switch to a hybrid QA algorithm, we are quite far from this being a viable option. CMS routinely needs to cluster many hundreds of thousands of vertices, which would require a number of qubits (vertices × tracks) far beyond what is currently feasible. However, our results demonstrate the flexibility of QA, where we didn't have to tune a radius parameter unlike anti-kt, and still achieved better results. Future work could explore extending this to curved tracks from charged particles.