PURDUE UNIVERSITY

DEPARTMENT OF PHYSICS AND ASTRONOMY

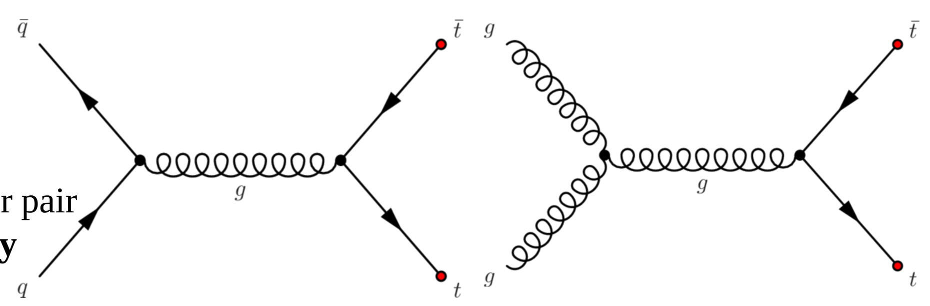
TOP QUARKS AS A PROBE TO QUANTUM INFORMATION

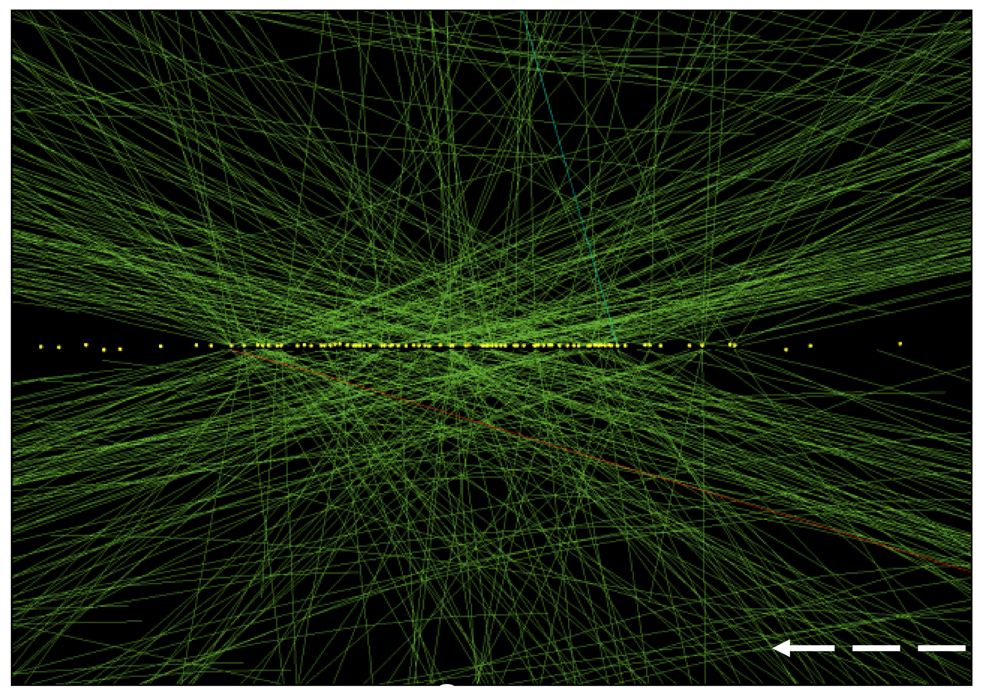
Souvik Das, Andrew J. Wildridge, Sachin B. Vaidya, Andreas Jung

ABSTRACT: Top quark pairs produced at the Large Hadron Collider (LHC) provide a unique window into quantum information theory at high energies. One of the most ubiquitous measurements of quantum information is the violation of Bell's inequality. We explore what would be necessary to observe a violation of Bell's inequality and the dependence of this on the initial state of the top quark pair. Furthermore, we show how a more general application of quantum information theory in the realm of quantum computing can be leveraged to perform offline reconstruction of primary vertices. We perform some optimizations of the running parameters of the quantum annealer and compare to a non-optimized performance. Lastly, we discuss the future outlook of both these topics and steps to be taken.

TOP QUARKS AS A PROBE TO QUANTUM INFORMATION

- Top quarks decay before hadronization
- Spin-information is preserved in decay products
- Measurement of **spin correlations** between ttbar pair can be used to perform a test of **Bell's inequality**
- A nice window into quantum information at high energies





Representative event in CMS with charged particle tracks from 78 collisions

- More generally, we can use a quantum computer for analysis
- Literally quantum information at the LHC, potentially
- Can try and solve offline reconstruction tasks with a quantum computer
- We tackled primary vertexing with a quantum annealer

BELL'S INEQUALITY

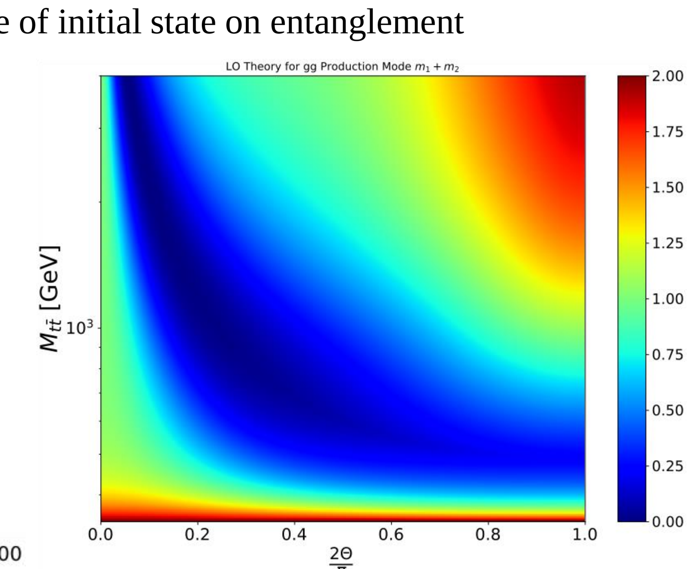
$$\left|\hat{n}_1 \cdot C \cdot (\hat{n}_2 - \hat{n}_4) + \hat{n}_3 \cdot C \cdot (\hat{n}_2 + \hat{n}_4)\right| \leq 2$$

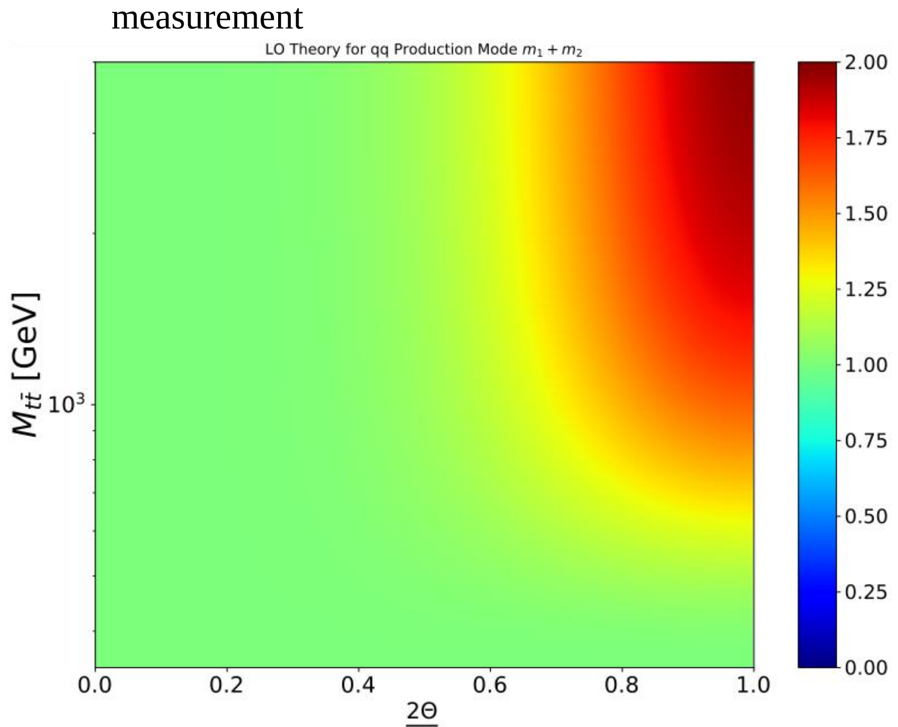
Generalized Bell's Inequality with Spin Correlation matrix C

- Can show that the above (generalized) Bell's inequality is equivalent to the sum of the two largest eigenvalues from the $C^T C$ matrix, denoted m_1 and m_2, being less than or equal to 1
- In other words, Bell's inequality is violated when $m_1 + m_2 > 1$
- Analytic solutions exist to LO for spin correlations for qqbar and gg initial states
- Can use these predictions to understand the dependence of initial state on entanglement

gg Initial State

- Strong entanglement/violation of Bell's inequality at threshold
- For large scattering angle and invariant mass also violate Bell's inequality
- Requires very good resolution near threshold and enough statistics in large mttbar for measurement





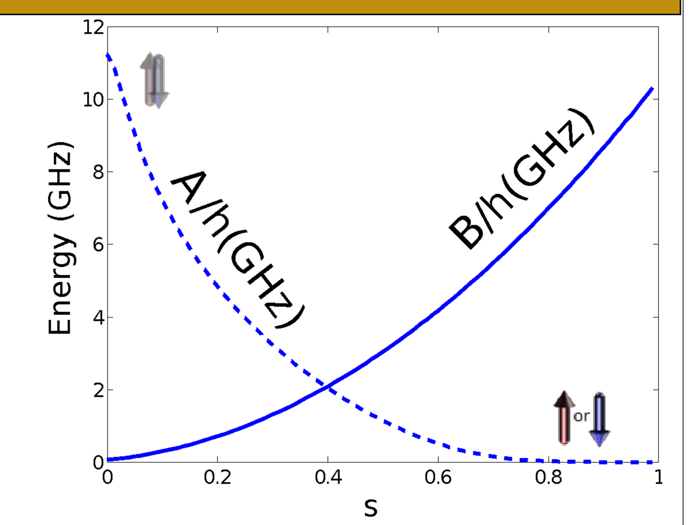
qqbar Initial State

- Always violates Bell's Inequality
- Strong signal still resides in the large scattering angle and mttbar region
- Easier initial state for measurement of Bell's Inequality
- Less statistics however for LHC

THE D-WAVE 2048 QUBIT QUANTUM COMPUTER

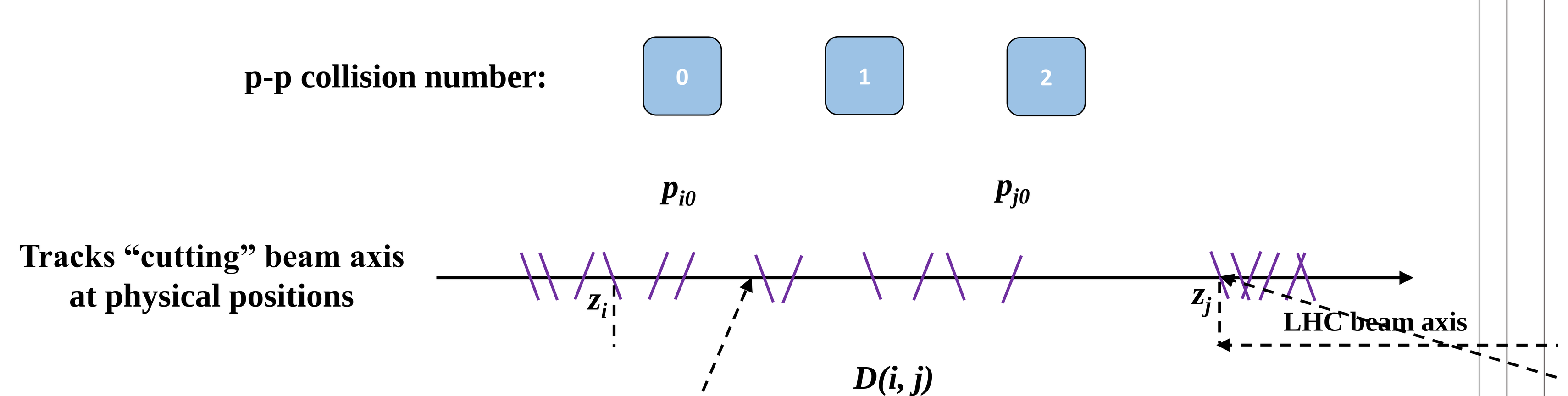
- **Adiabatic quantum computing** exploits:
  A system in ground state of a Hamiltonian evolves to ground state of perturbed Hamiltonian if perturbation is slow
- **Quantum annealing** is a practical approximation to adiabatic quantum computing in finite time, open system. Finds low-energy states of interacting spin system using thermally-assisted quantum tunneling

$$H_p = \sum_i h_i \sigma_z^i + \sum_i \sum_{j>i} J_{ij} \sigma_z^i \sigma_z^j,$$



$$H = A(s) \sum_i \sigma_x^i + B(s) H_p,$$

PROBLEM FORMULATION AND OPTIMIZATION



- Objective function we minimize for clustering tracks to collisions is naturally in QUBO form
  - p_{ik} is binary probability of track i associated with collision k. **Represented by a qubit**
  - $D(i, j)$ is measure of distance between tracks i and j. Uncertainties of track reconstruction are included
  - λ enforces one track associated to one collision. Optimal $\lambda = 1.2 \times \max(D(i, j))$
  - $g(x; m)$ distorts $D(i, j)$ to increase smaller values, thus making intermediate states approximately equidistant depending on m. Seen to

$$H_p = \sum_k^{n_V} \sum_i^{n_T} \sum_{j>i}^{n_T} p_{ik} p_{jk} g(D(i,j); m)$$
$$+ \lambda \sum_i^{n_T} \left(1 - \sum_k^{n_V} p_{ik}\right)^2,$$

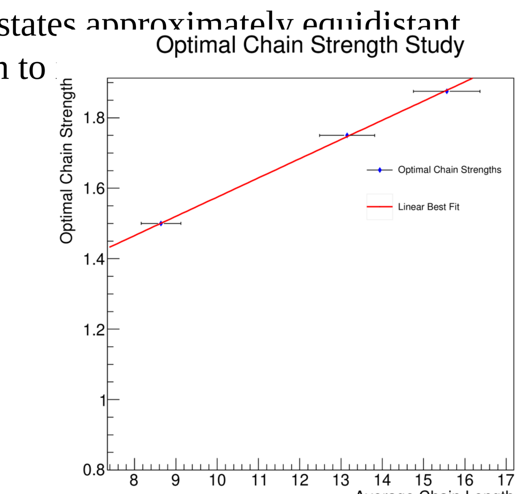
Problem Hamiltonian in QUBO form

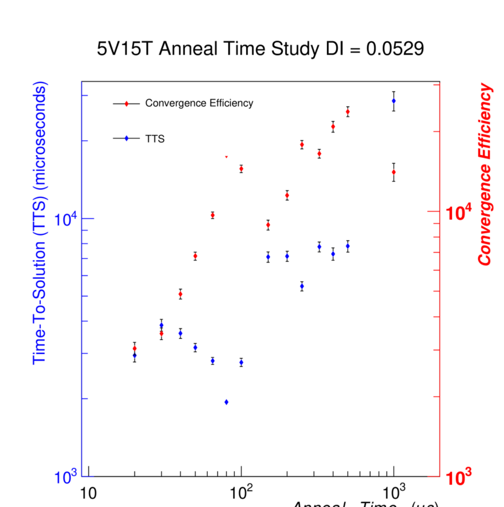
$$D(i,j) = \frac{|z_i - z_j|}{\sqrt{\delta z_i^2 + \delta z_j^2}}.$$

Distance measure between tracks

$$g(x; m) = 1 - e^{-mx},$$

Distortion function to optimize convergence



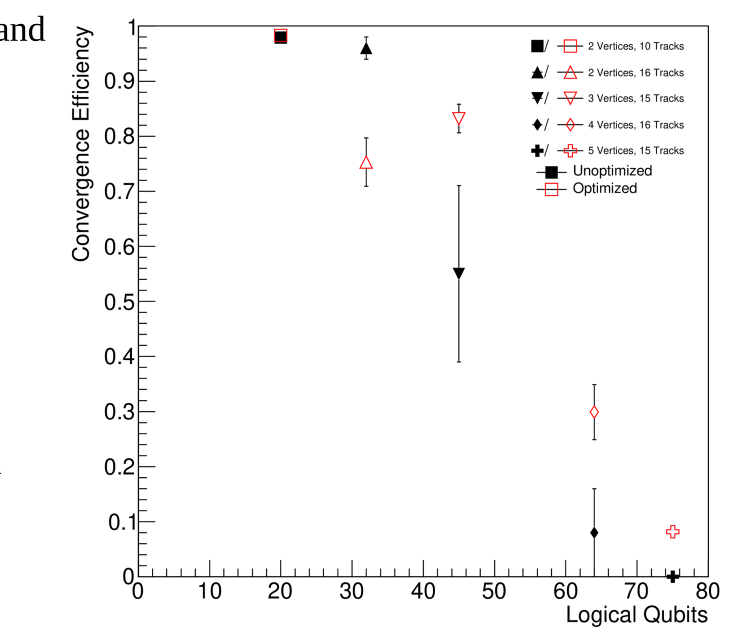


- Found deterministic embedding algorithm
- Optimized coupling strength between physical qubits representing a logical qubit
- Found linear relationship between average chain length in the embedding and optimal chain strength
- Optimized the amount of anneal time given the quantum annealer by minimizing a metric called Time-To-Solution (TTS)
- TTS calculates how much total anneal time would be required to obtain a correct solution with 95% probability given some anneal time t and efficiency ε

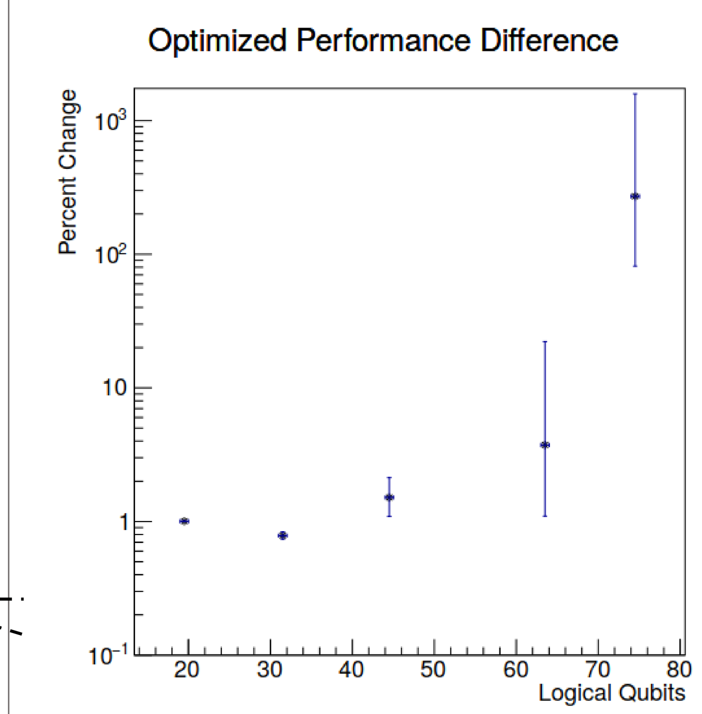
Optimizations performed on the quantum annealer. Top Left: Optimized embedding from logical qubits to physical qubits. Each shade of color represents a logical qubit. Each node is a physical qubit. Top Right: Chain strength optimization of the chains in the embedding. Bottom: Anneal time optimization plot. Lower TTS is better.

RESULTS

- Algorithm tested on artificial events drawn from simulated and measured LHC distributions of collision positions and tracks
- Realistic track reconstruction uncertainties used CMS Collaboration, JINST 9 (2014) P10009
- Solution's p_{ik} is track association to p-p collisions. Combined with z_i and δz_i, collision positions can be estimated
- Intermediate results show decreasing performance with problem complexity



Comparison of convergence efficiency for various event topologies of 100 events each



- Looked at impacts of optimizing the embedding, chain strengths, and anneal time on a lower noise QPU
- **Very large improvements** for complex event topologies

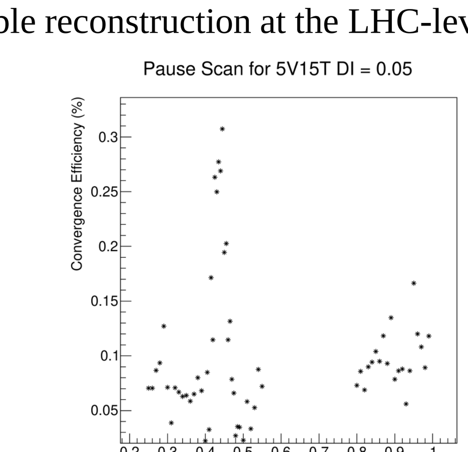
CONCLUSIONS AND OUTLOOK

Track clustering, first step of vertexing at the LHC, finds a natural implementation on a quantum annealer.
- Track association to p-p collision recovered
- p-p collision positions reconstructed from track positions that belong to a collision

Bell's inequality, a long-standing pillar of quantum information theory, is an accessible measurement at the LHC using top quark pairs
- Highly dependent on initial state

Future Outlook – Primary Vertexing
- Other optimizations such as reverse annealing, anneal pauses, and anneal offsets exist
- Some of these have been performed and show very large performance gains on complex event topologies
- Utilizing the new Pegasus architecture can enable for exploration of larger event topologies
- Exploration of hierarchical clustering techniques to enable reconstruction at the LHC-level complexity

Future Outlook – Bell's Inequality
- Bell's inequality represents a challenging measurement in the top quark sector
- Requires a triple differential measurement of 9 observables that are then combined into a single observable via non-linear operations
- Would require a novel/advanced application of unfolding to parton level
- Likely sensitive to systematics



A scan of starting point of a pause during the anneal for 5V15T, ~1000x improvement over intermediate result alone

Publication: Track clustering with a quantum annealer for primary vertex reconstruction at hadron colliders

https://arxiv.org/abs/1903.08879