Leveraging a quantum annealer to identify event-topology at high energy colliders

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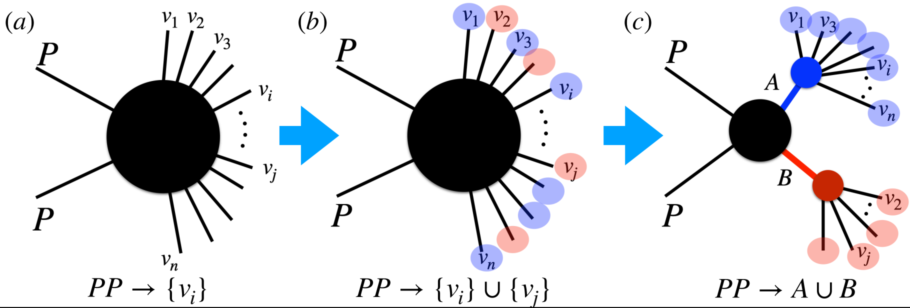
Ref.

- Minho Kim, Pyungwon Ko, JhP, Myeonghun Park, 2111.07806

Bottom-up approach to identify event topology



- Consider a 2 → 2 process: $PP \to AB$
- A and B decay to “jets”: $j_1, \cdots, j_n$ $(= v_1, \cdots, v_n$ in Fig.)
- Which jets are from A? Likewise for B?

Binary classification as QuadraticUnconstrainedBinaryOptimization

- Label j_i with $x_i \in \{0, 1\}$
- j_i is (assumed to be) from $\{A, B\}$ if $x_i = \{1, 0\}$
- With $\{P_1, P_2, p_i\}$ being 4-momenta of $\{A, B, j_i\}$

$$P_1 = \sum_i p_i x_i, \quad P_2 = \sum_i p_i (1 - x_i)$$

- Minimize

$$H(x_i) = (P_1^2 - P_2^2)^2 + \lambda(P_1^2 + P_2^2)$$

  with an appropriately chosen λ
- Classically, a search of 2^n possibilities of $\{x_i\}$

Ising model for QUBO

- Change variables: $x_i = (1 + s_i)/2$
- Quantum annealer finds ground state of

$$H(s_i) = \sum_{ij} J_{ij} s_i s_j + \sum_i h_i s_i$$

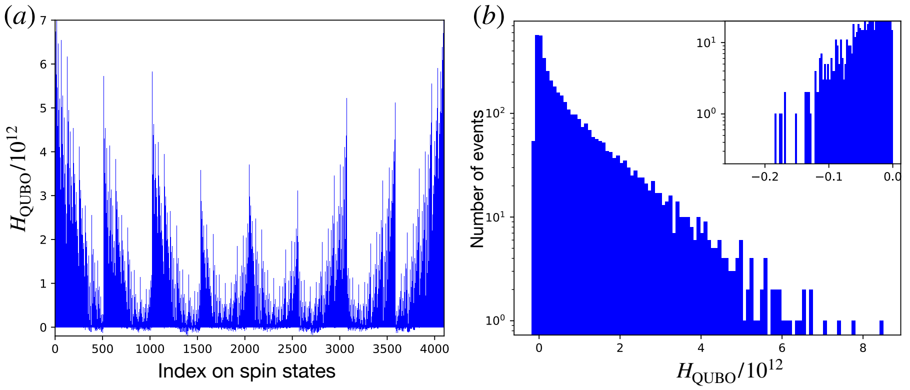
where

$$J_{ij} = \sum_{k\ell} p_i \cdot p_k \, p_j \cdot p_\ell + 2\lambda \, p_i \cdot p_j$$

$$h_i = 2 \sum_j \sum_{k\ell} (p_i \cdot p_k \, p_j \cdot p_\ell - p_k \cdot p_\ell \, p_i \cdot p_j) - 2\lambda \sum_j p_i \cdot p_j$$

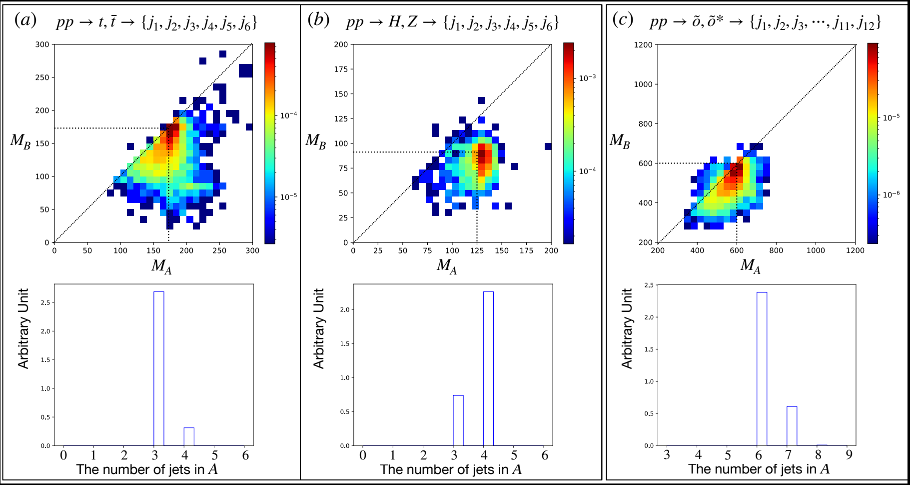
Energy spectrum of H for a four-top event

$$pp \to \tilde{o}, \tilde{o}^* \to t, \bar{t}, t, \bar{t} \to \{j_1, j_2, j_3, \ldots, j_{10}, j_{11}, j_{12}\}$$

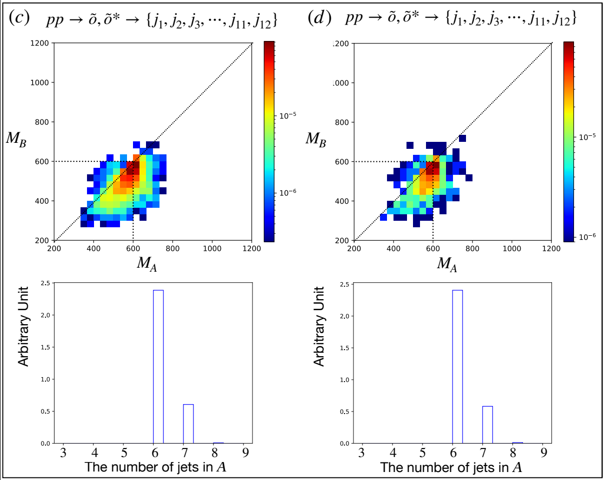


- Complicated structure hinders global minimum finding by an iterative algorithm
- Complexity of full scan is $\mathcal{O}(2^n)$
- Complexity of parameters preparation for QA is $\mathcal{O}(n^2)$

Results from full scans



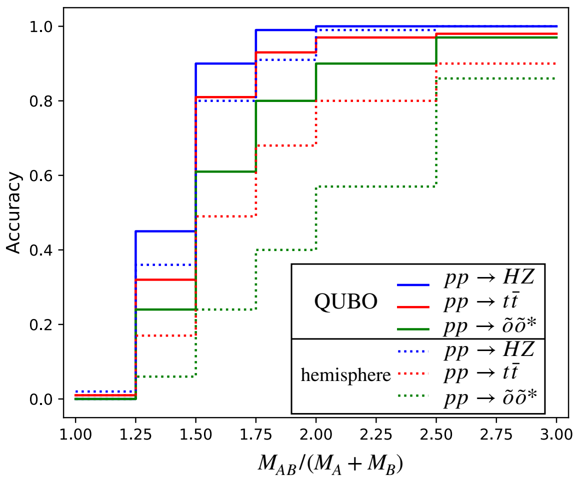
Full scan (c) vs quantum annealing (d)



- For (d), we used D-Wave Advantage™ system

Comparison with an existing algorithm

Matching accuracy



- QUBO algorithm performs better at low boosts thanks to its seedless nature

Summary

Quantum annealing for identifying topology of collider events in a bottom-up approach

- Combinatorial problem is reduced to QUBO which is solved by a quantum annealer
- Complexity $\sim \mathcal{O}(n^2)$ as n (= number of jets) grows
- Possible further speedup via parallel annealing
- Results in better matching accuracy than (existing) hemisphere method