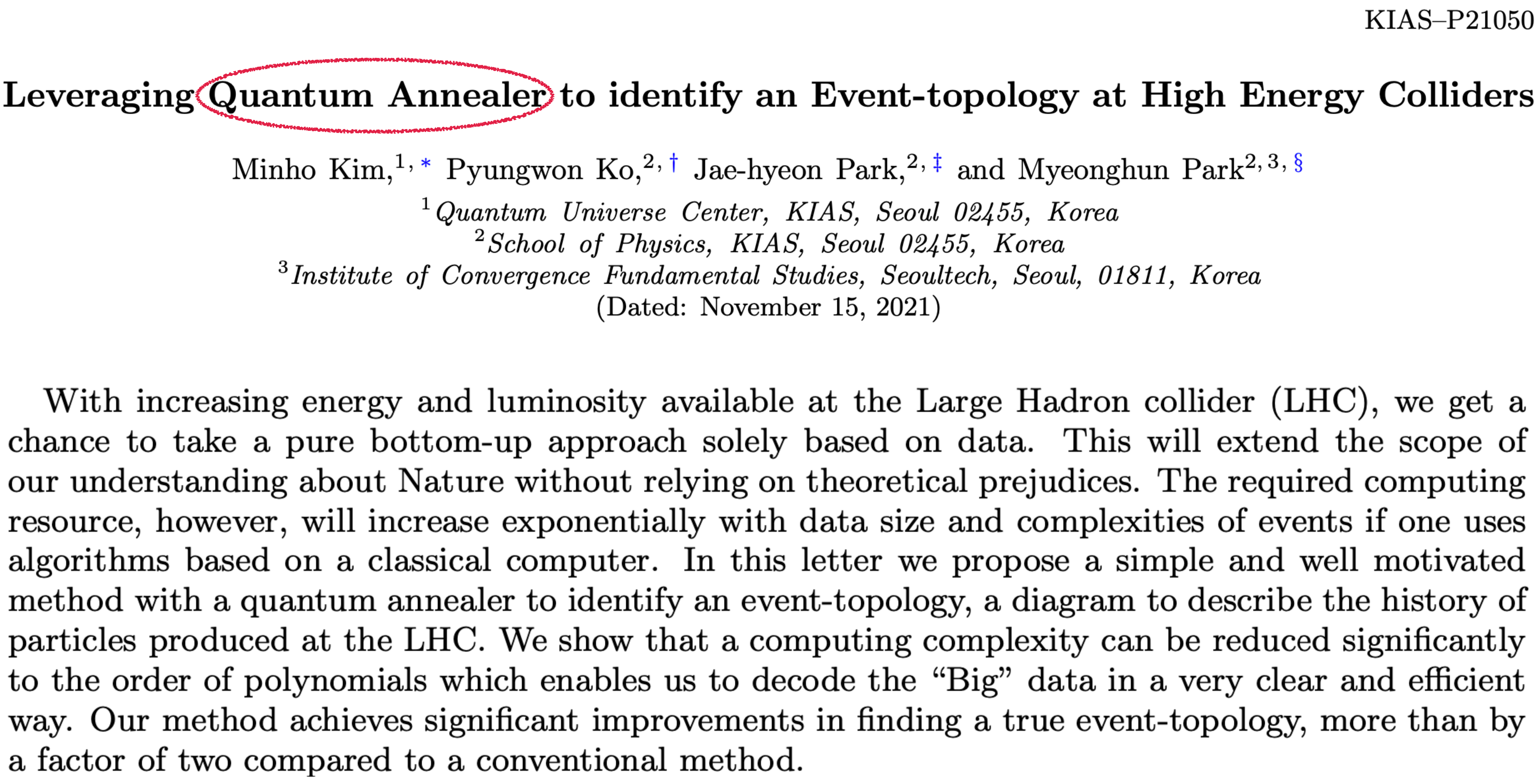
Identifying an event topology with a quantum annealer

Dong Woo Kang (KIAS)

QTI-TH Forum, 16 March 2023

https://arxiv.org/abs/2111.07806



KIAS–P21050

Leveraging Quantum Annealer to identify an Event-topology at High Energy Colliders

Minho Kim,[1,*] Pyungwon Ko,[2,†] Jae-hyeon Park,[2,‡] and Myeonghun Park[2,3,§]
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(Dated: November 15, 2021)

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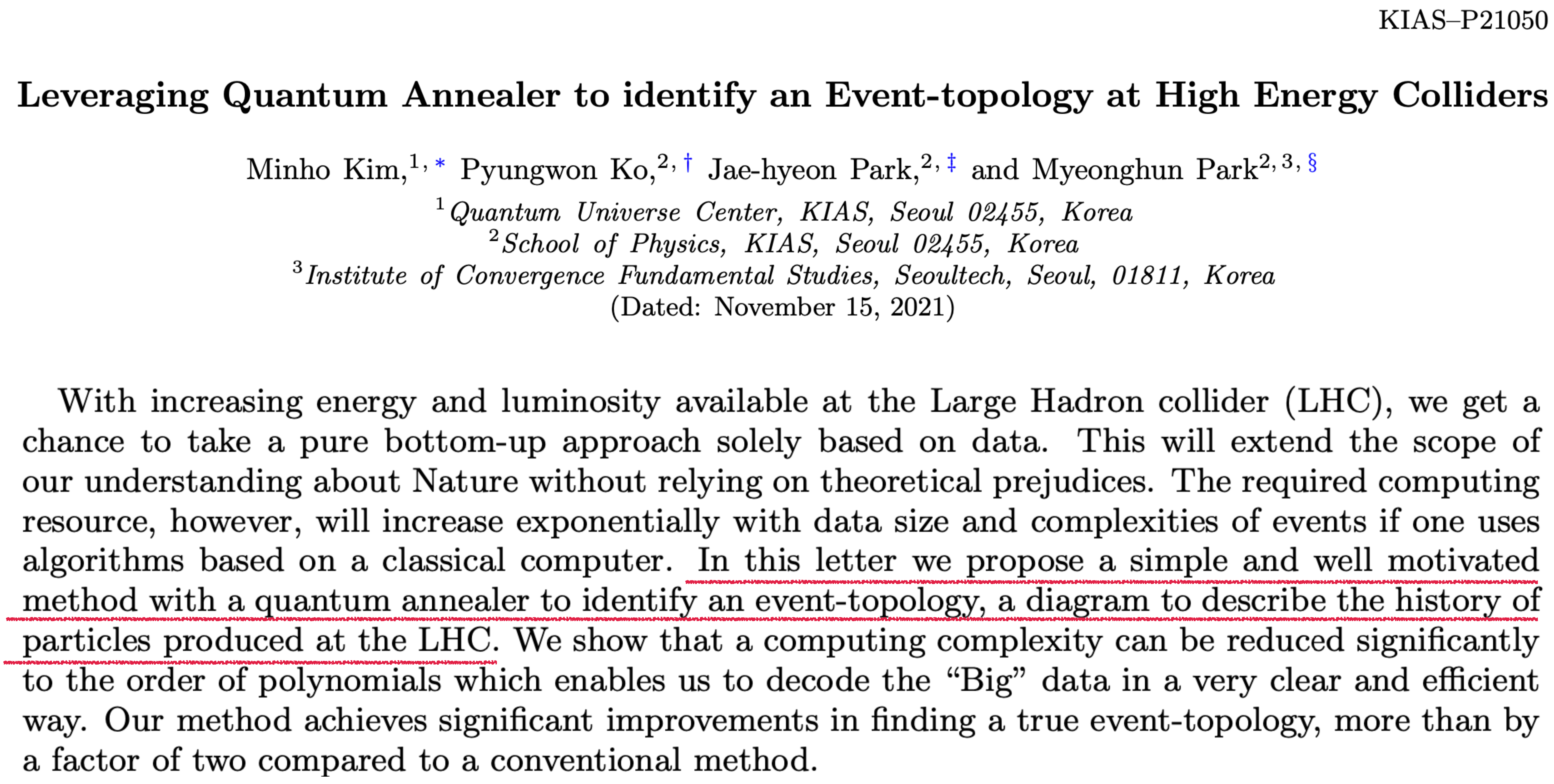

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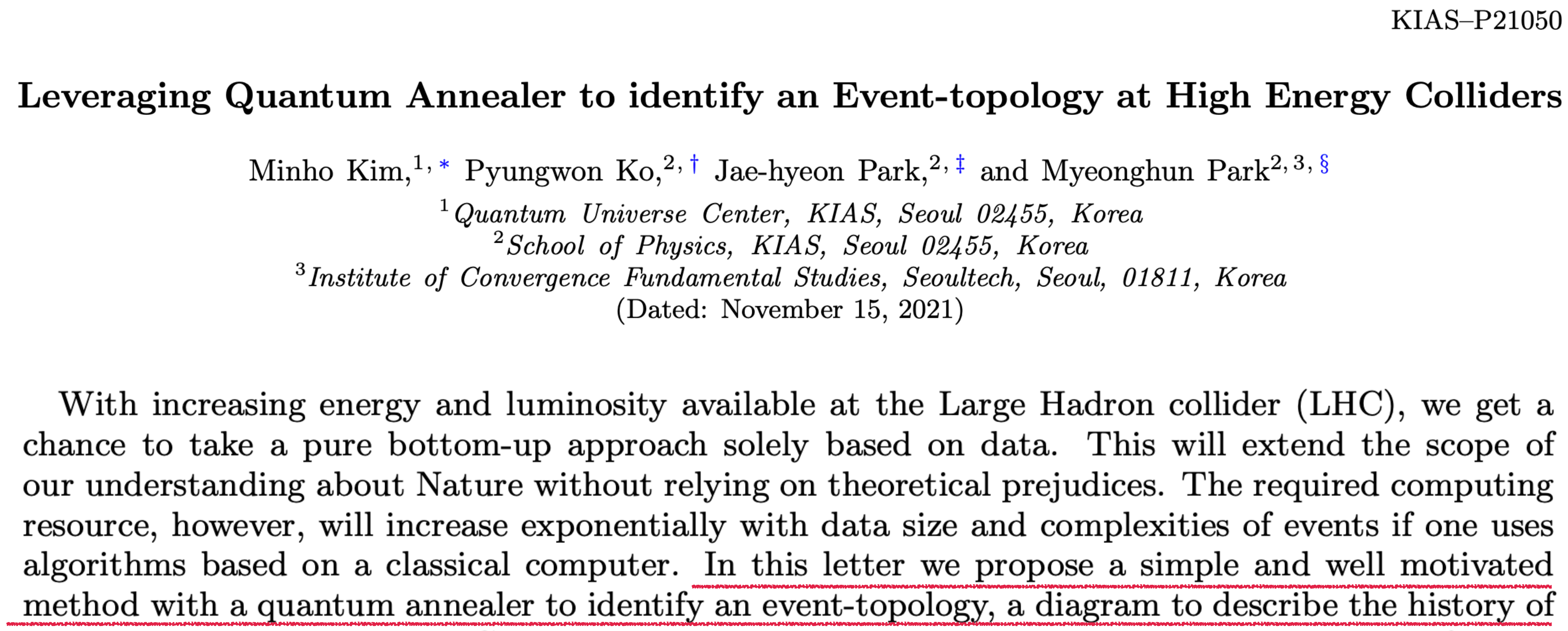

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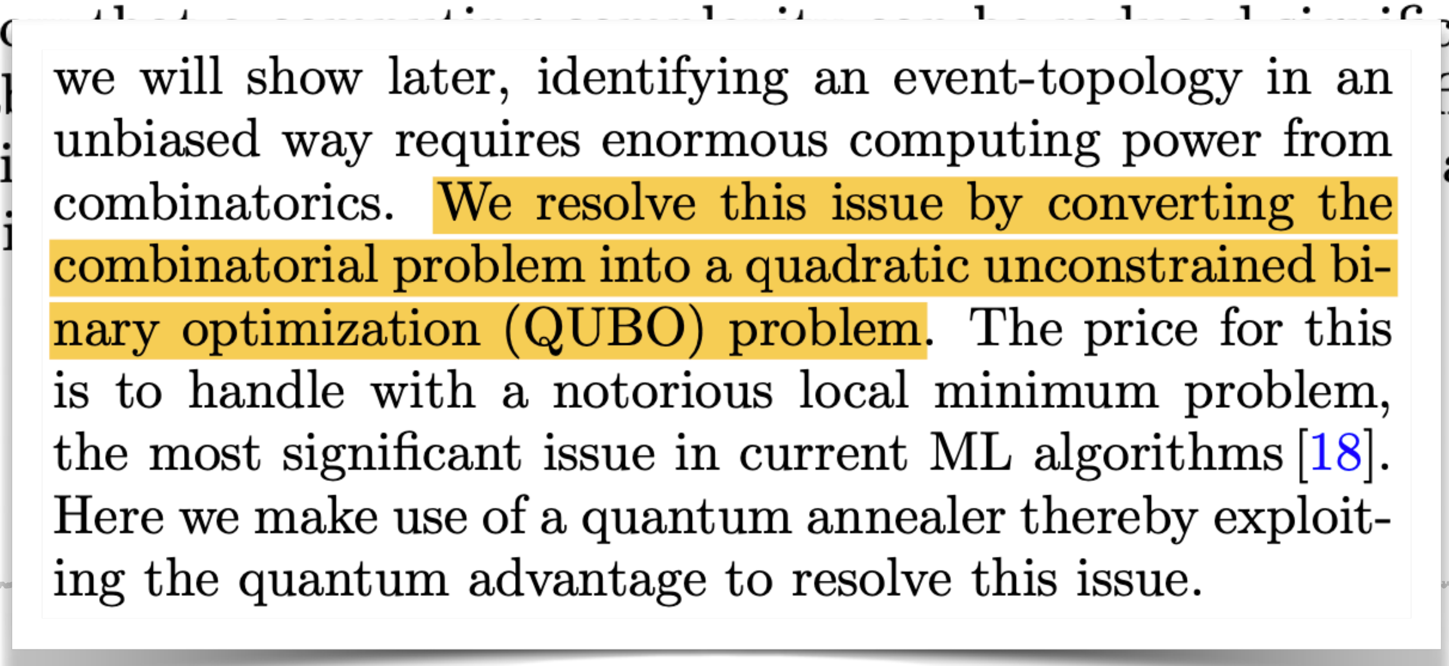

we will show later, identifying an event-topology in an unbiased way requires enormous computing power from combinatorics. We resolve this issue by converting the combinatorial problem into a quadratic unconstrained binary optimization (QUBO) problem. The price for this is to handle with a notorious local minimum problem, the most significant issue in current ML algorithms [18]. Here we make use of a quantum annealer thereby exploiting the quantum advantage to resolve this issue.

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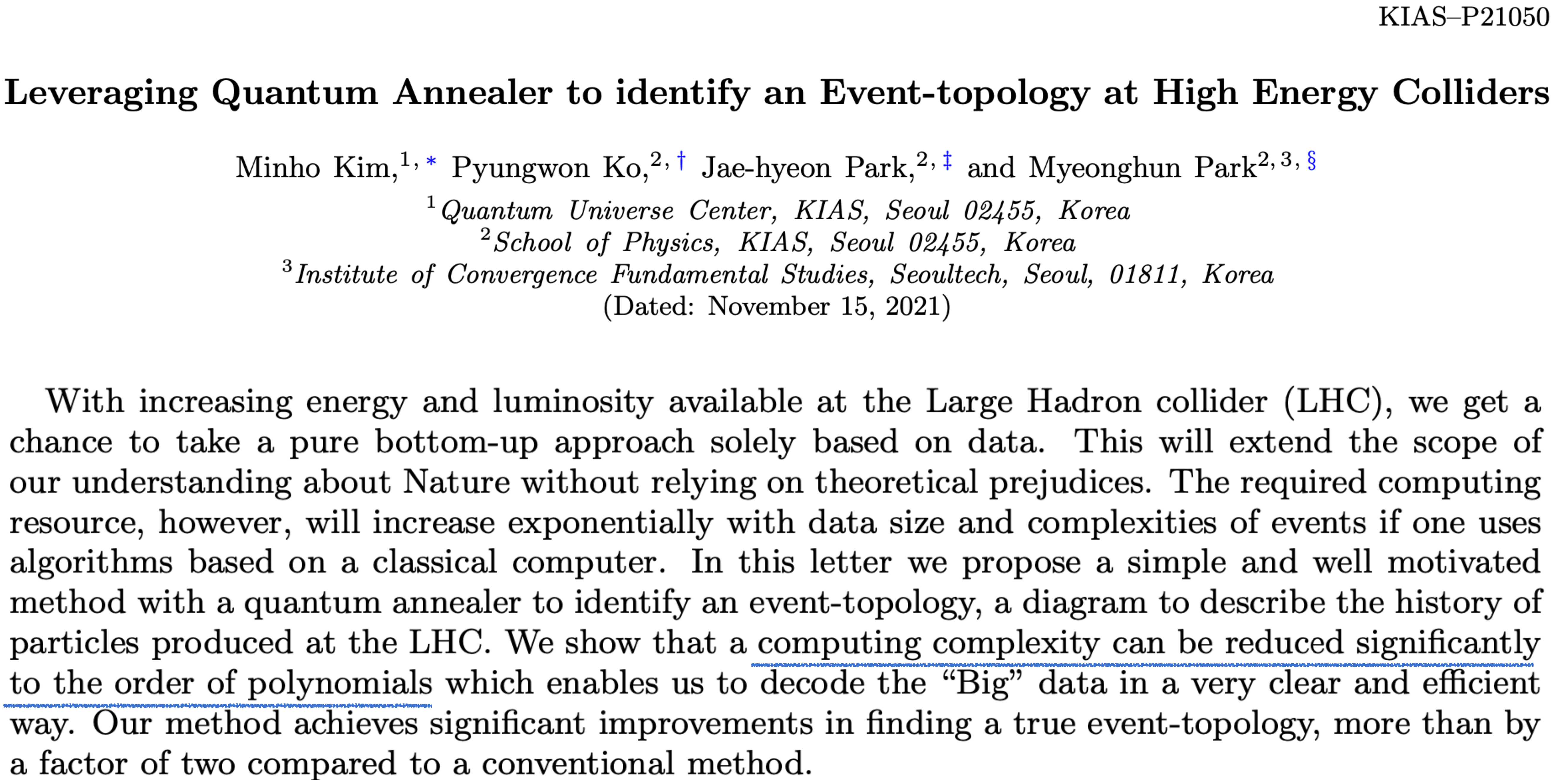

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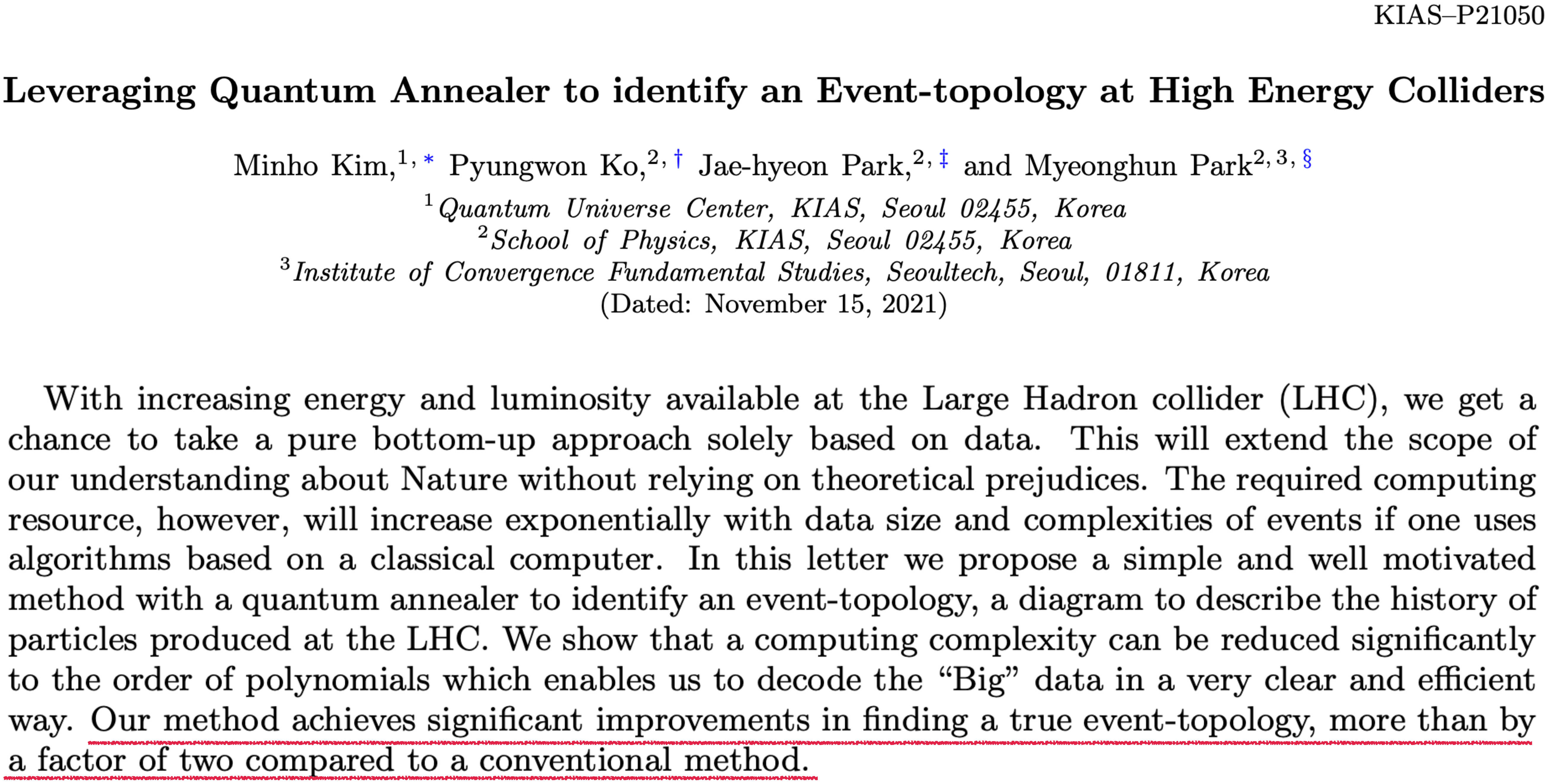

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Quantum Annealer

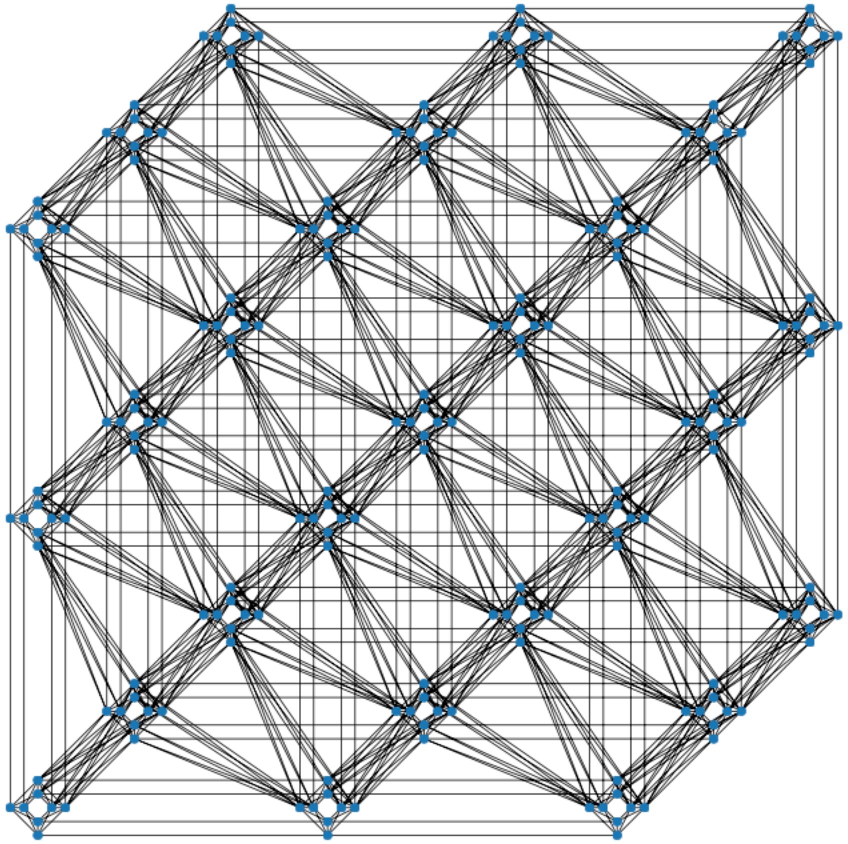
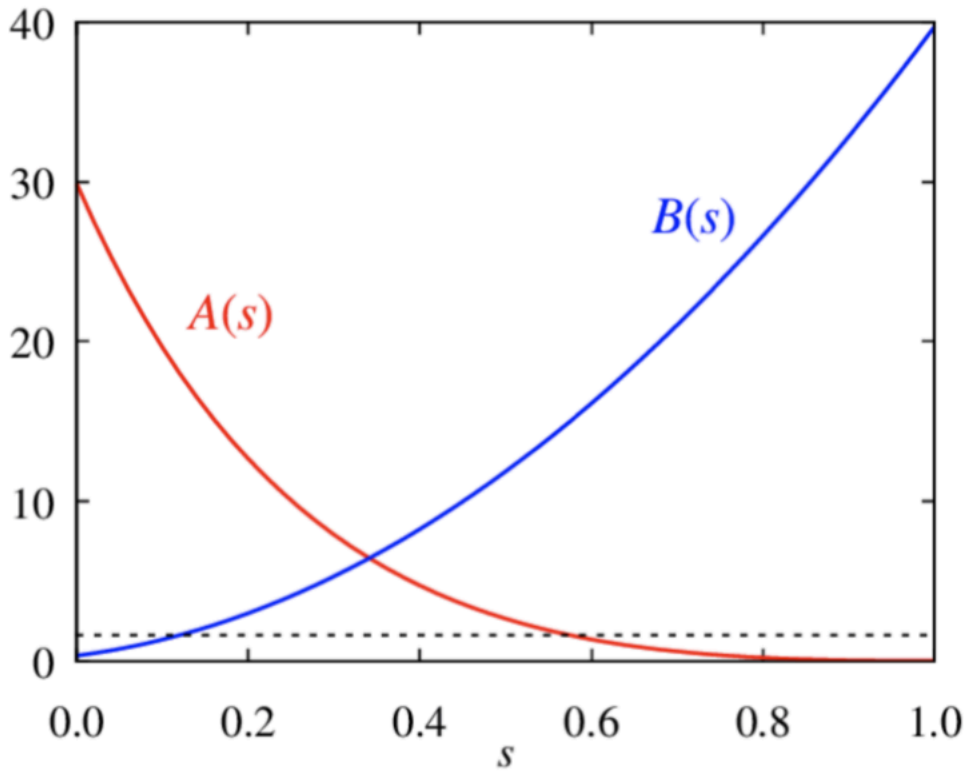


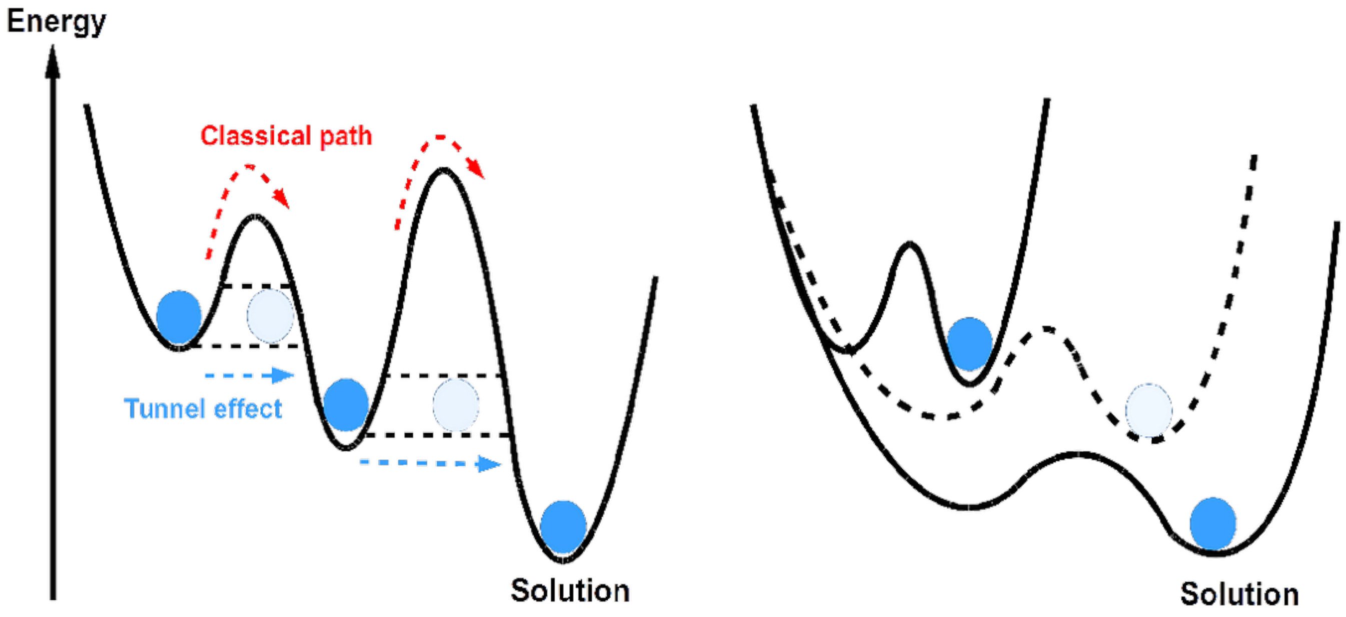
FIG. 7. A Pegasus graph with 27 unit cells.

Quantum Annealing

With adiabatic theorem, we can find the ground state of a complicated H_{QUBO} starting from simple Hamiltonian H_0

$$H_{\mathrm{QA}}(t) = A(t)\,H_0 + B(t)\,H_{\mathrm{QUBO}}$$





Quantum Tunnelling **Adiabatic evolution**

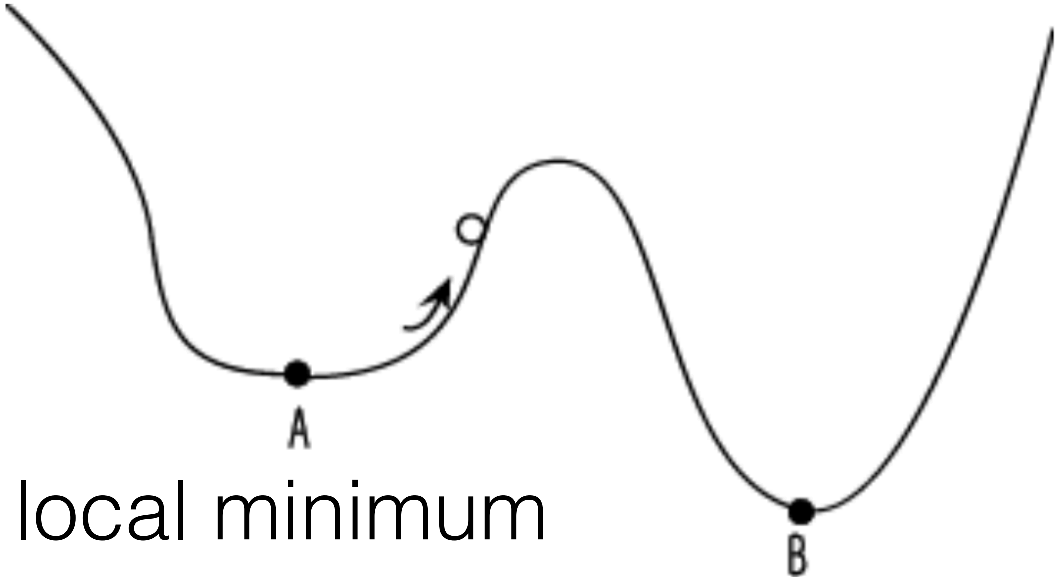
QUBO?

Claims to utilize “quantum tunneling” to find the minimum of the Hamiltonian

$$H_{\mathrm{QUBO}} = \sum J_{ij}\sigma_i\sigma_j + \sum h_i\sigma_i$$

for **Q**uadratic **U**nconstrained **B**inary **O**ptimization problems

"Classic" minimization method (for Ising hamiltonian)

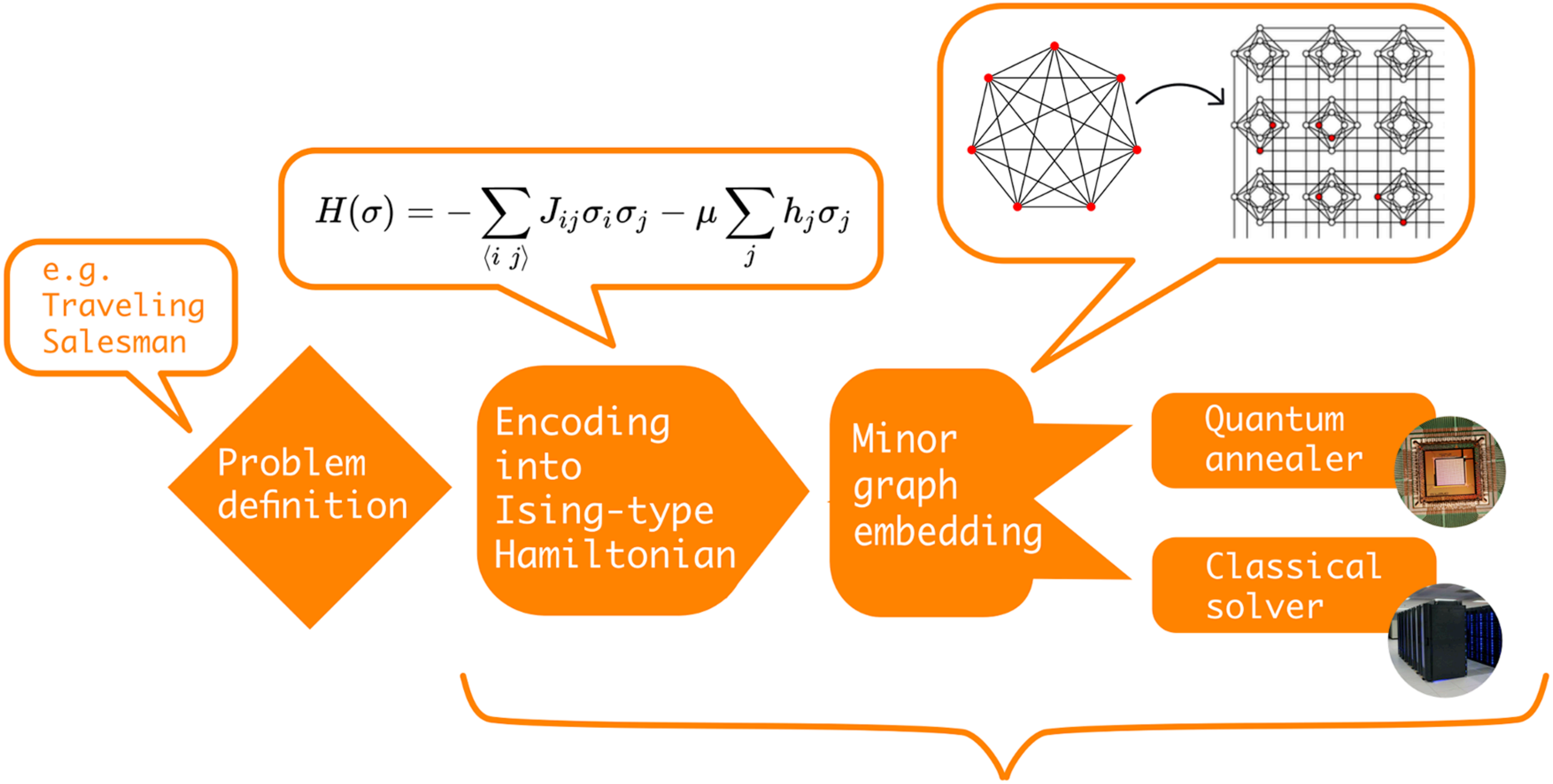


Simulated annealing

- Go to the next spin state $s_n \rightarrow s_{n+1}$
  1) If $E_n > E_{n+1}$: go to the lower energy
  2) If $E_n < E_{n+1}$, go with a probability of $e^{-\frac{E_{n+1} - E_n}{k_B T}}$ to **jump out**

(A "temperate $T \rightarrow 0$. With large T, SA can jump out local minimum)

QA workflow of Quantum Annealer



e.g.
Traveling
Salesman

$$H(\sigma) = -\sum_{\langle i\ j \rangle} J_{ij}\sigma_i\sigma_j - \mu \sum_j h_j \sigma_j$$

Problem definition

Encoding into Ising-type Hamiltonian

Minor graph embedding

Quantum annealer

Classical solver

Full-stack

Problem in High Energy Physics

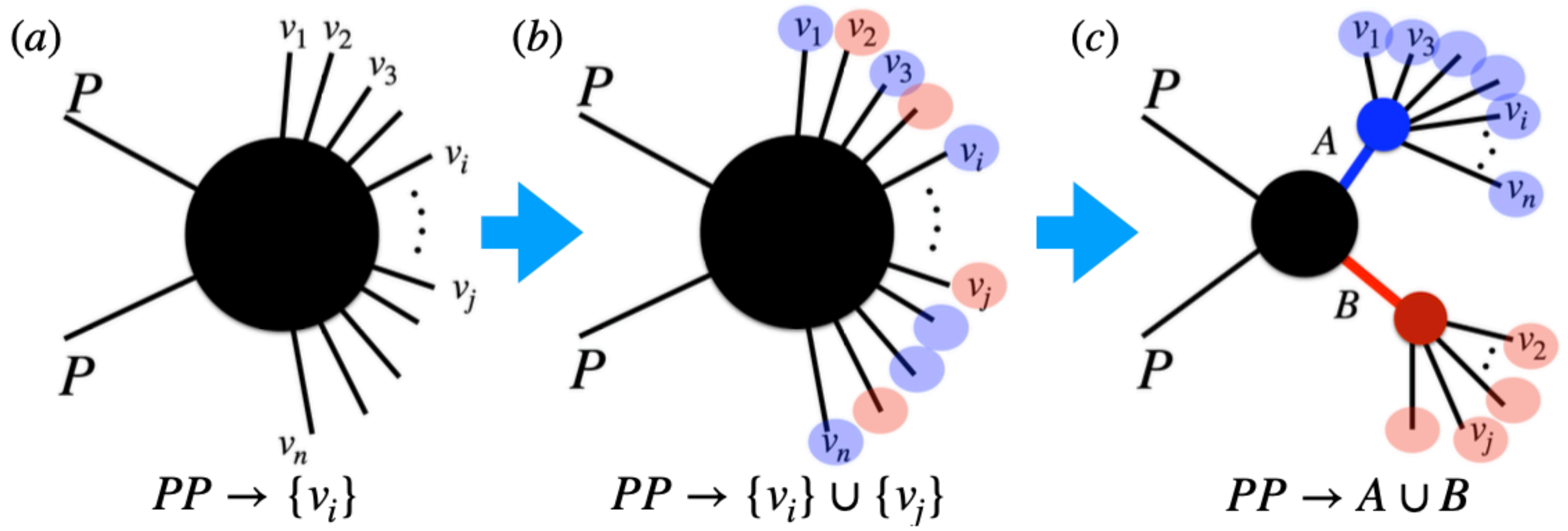


FIG. 1. (a) n-observed particles (b) Dividing n particles into two groups for 2 → 2 process (c) Identified event-topology with A and B.

Q1. What is the relevant event-topology behind anomalous events?

Q2. Mass spectrum?

Q3. Spin configuration?

Problem in High Energy Physics

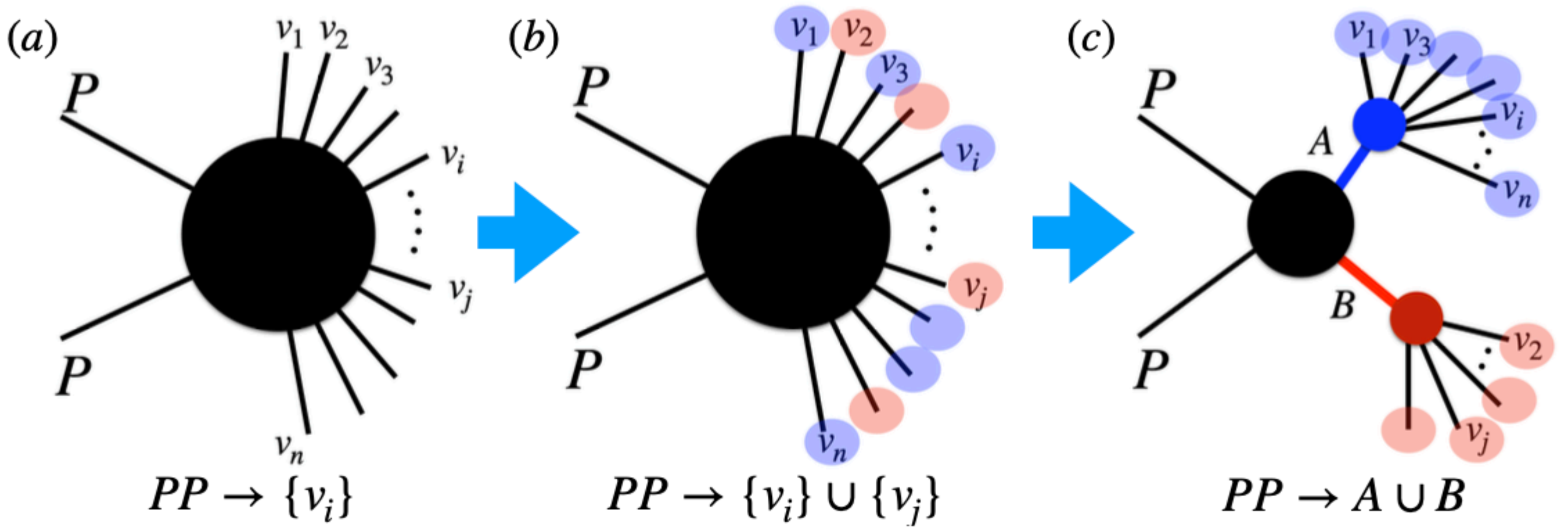


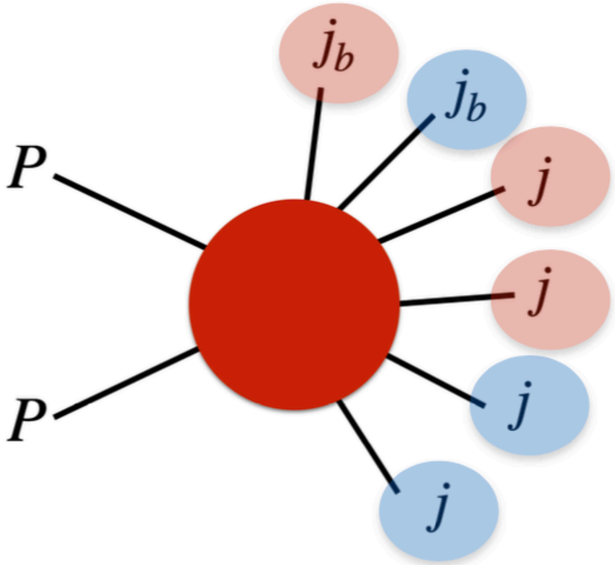
FIG. 1. (a) n-observed particles (b) Dividing n particles into two groups for 2 → 2 process (c) Identified event-topology with A and B.

1. Under the simple assumption $PP \to AB \to \{\nu_i\}\{\nu_j\}$

2. Find a right combination to reconstruct A and B particles

3. Read out the masses and spins from event reconstruction.

Example event topologies



- Standard example of six jets

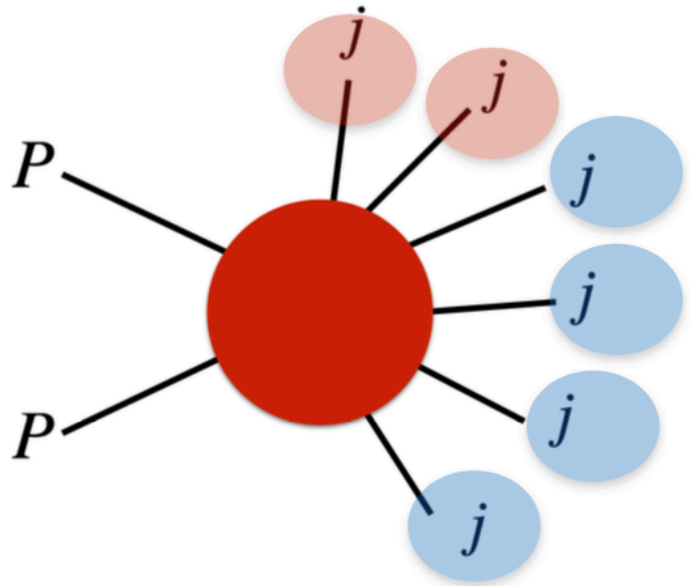
  $pp \to t\bar{t} \to \{j_b, (W \to jj)\} \cup \{j_b, (W \to jj)\}$

  (when A and B have same mass)

- Right answer is $(n_A, n_B) = (3,3)$

$2^6 = 64$ cases,
no special assignment
for b-jet

Example event topologies



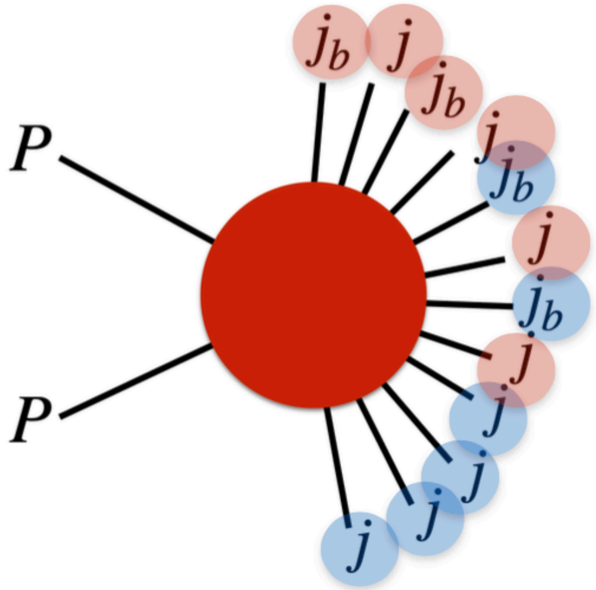
- Different mother particles

$$pp \to ZH \to \{j, j\} \cup \{(W \to jj), (W^* \to jj)\}$$

- Right answer is $(n_A, n_B) = (2{,}4)$

$2^6 = 64$ cases,
no special assignment
for b-jet

Example event topologies



- Complicate situation (12 jets)

$$pp \to o\tilde{o} \to \{t, \bar{t}\} \cup \{t, \bar{t}\}$$

$$o \to t\bar{t} \to \{j_b, (W \to jj)\} \cup \{j_b, (W \to jj)\}$$

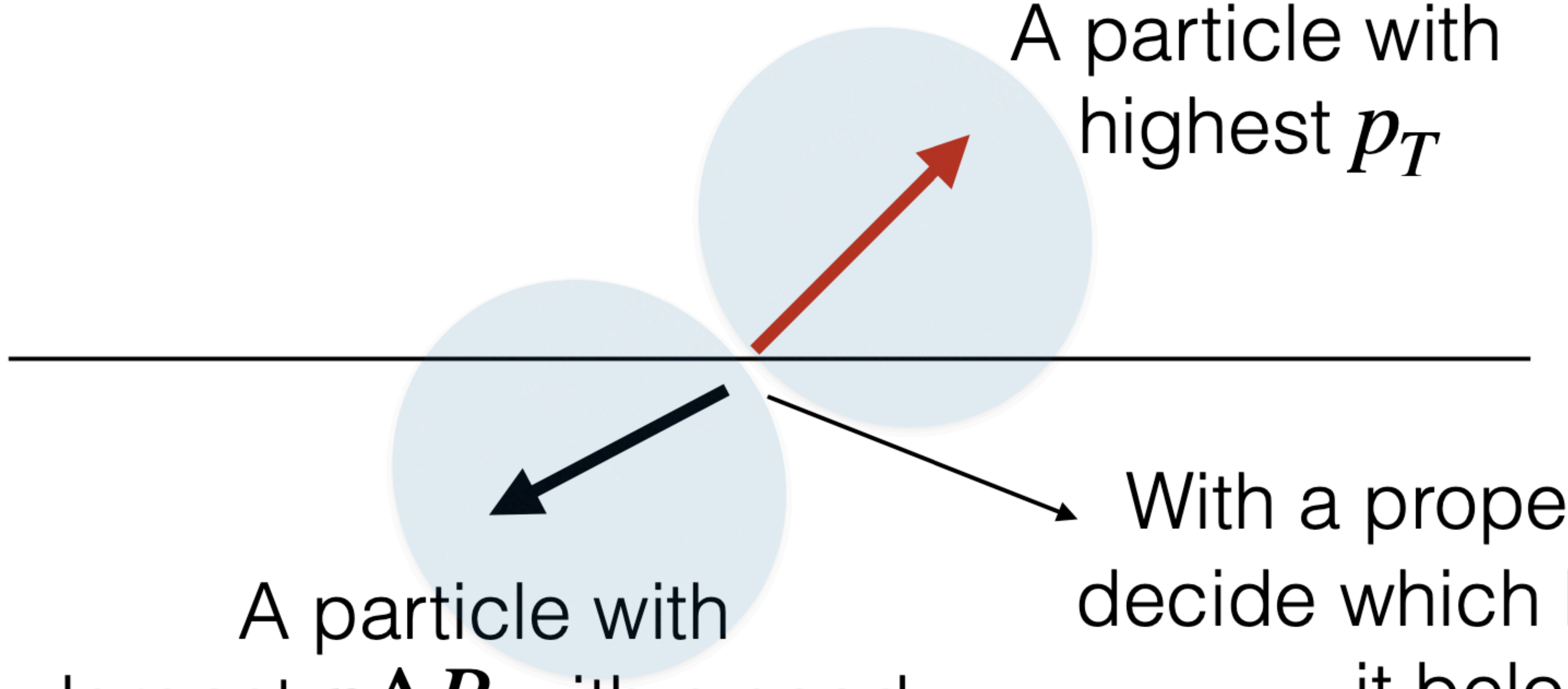
$$\tilde{o} \to t\bar{t} \to \{j_b, (W \to jj)\} \cup \{j_b, (W \to jj)\}$$

$2^{12} = 4096$ cases,
no prior knowledge on
a decay-structure

Combinatorial explosion exponentially

Classical algorithm

Hemisphere method: a seed-based method (iterative and converge)



A particle with highest p_T

With a proper metric d, decide which hemisphere it belongs

A particle with largest $p\Delta R$ with a seed

CMS hemisphere TDR,
Shigeki Matsumoto, Mihoko M Nojiri, and Daisuke Nomura (2006)

Encoding in to H_{QUBO}

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

$$H = (P_1^2 - P_2^2)^2 \;= (M_A^2 - M_B^2)^2$$

Try to minimize the mass difference

How can we deal with the gas of $M_A \neq M_B$?

Add regularized term $\lambda(P_1^2 + P_2^2)$

Encoding in to H_{QUBO}

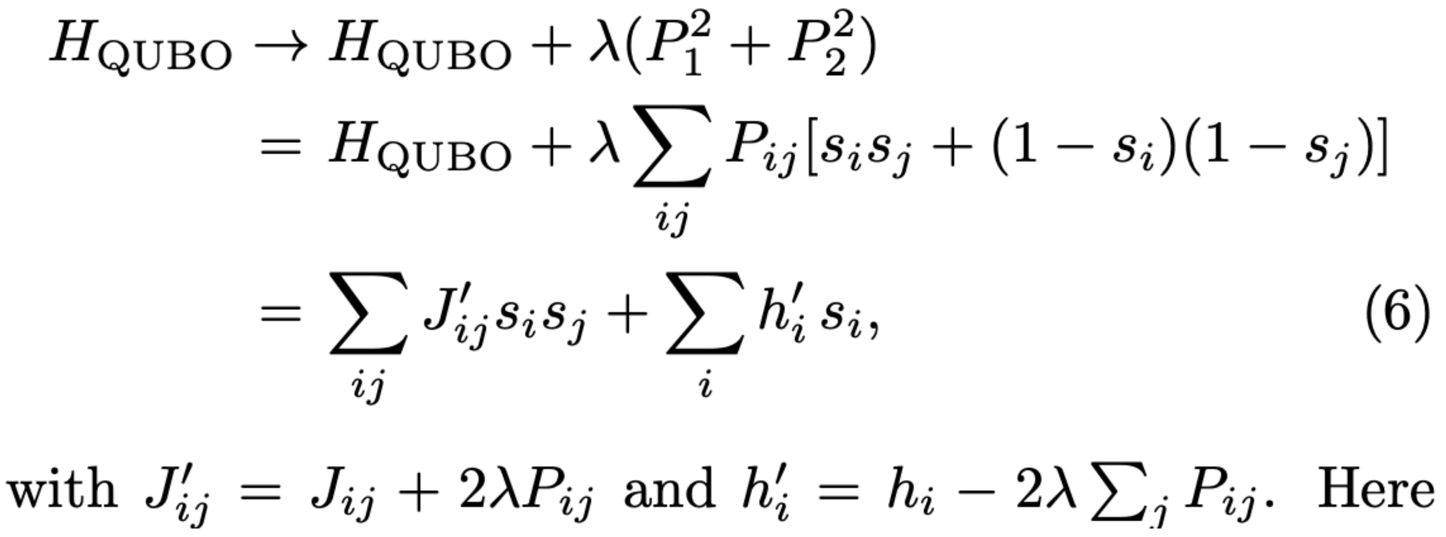
$$P_1 = \sum_i p_i\, x_i,\;\; P_2 = \sum_i p_i\,(1 - x_i),$$

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

$$H_{\text{QUBO}} = \sum J_{ij}\sigma_i\sigma_j + \sum h_i\sigma_i$$

$$J_{ij} = \sum_{k\ell} P_{ik}P_{j\ell},$$

$$h_i = 2\sum_j\Big[\sum_{k\ell}(P_{ik}P_{j\ell} - P_{k\ell}P_{ij})\Big],$$



$$\begin{aligned} H_{\text{QUBO}} &\to H_{\text{QUBO}} + \lambda(P_1^2 + P_2^2) \\ &= H_{\text{QUBO}} + \lambda\sum_{ij} P_{ij}[s_i s_j + (1 - s_i)(1 - s_j)] \\ &= \sum_{ij} J'_{ij} s_i s_j + \sum_i h'_i\, s_i, \end{aligned} \qquad (6)$$

with $J'_{ij} = J_{ij} + 2\lambda P_{ij}$ and $h'_i = h_i - 2\lambda\sum_j P_{ij}$. Here

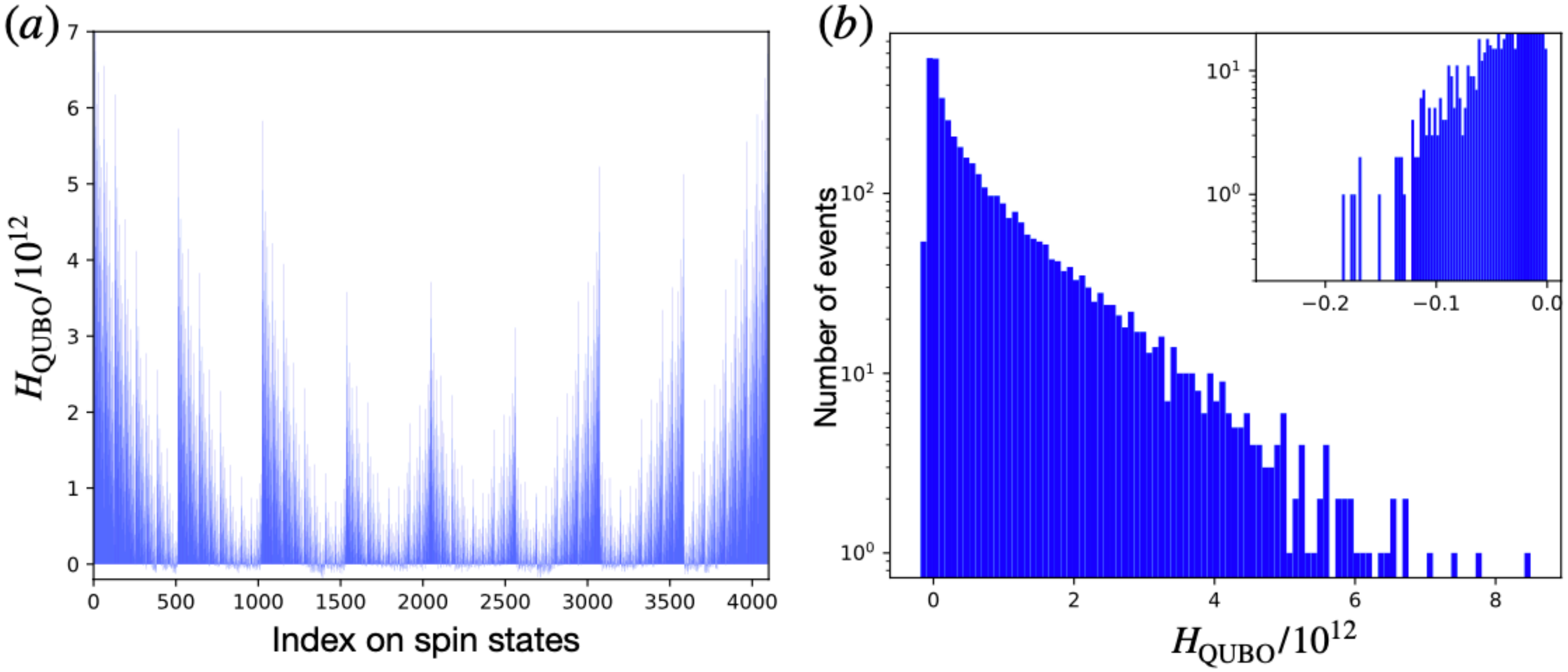
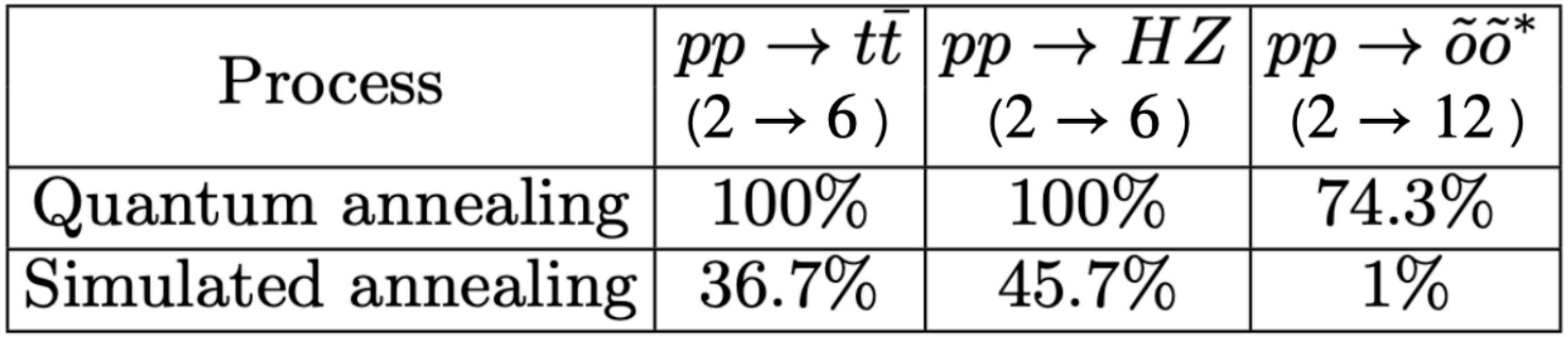


FIG. 2. We choose an event from detector level MC samples of EEq.q. (7c) to calculate (a) energy spectrum of H_{QUBO} with increasing indices of spin states, (b) histogram of energy spectrum of H_{QUBO} for all possible $2^{12} (= 4096)$ spin states.



Process	$pp \to t\bar{t}$ $(2 \to 6)$	$pp \to HZ$ $(2 \to 6)$	$pp \to \tilde{o}\tilde{o}^*$ $(2 \to 12)$
Quantum annealing	100%	100%	74.3%
Simulated annealing	36.7%	45.7%	1%

Results

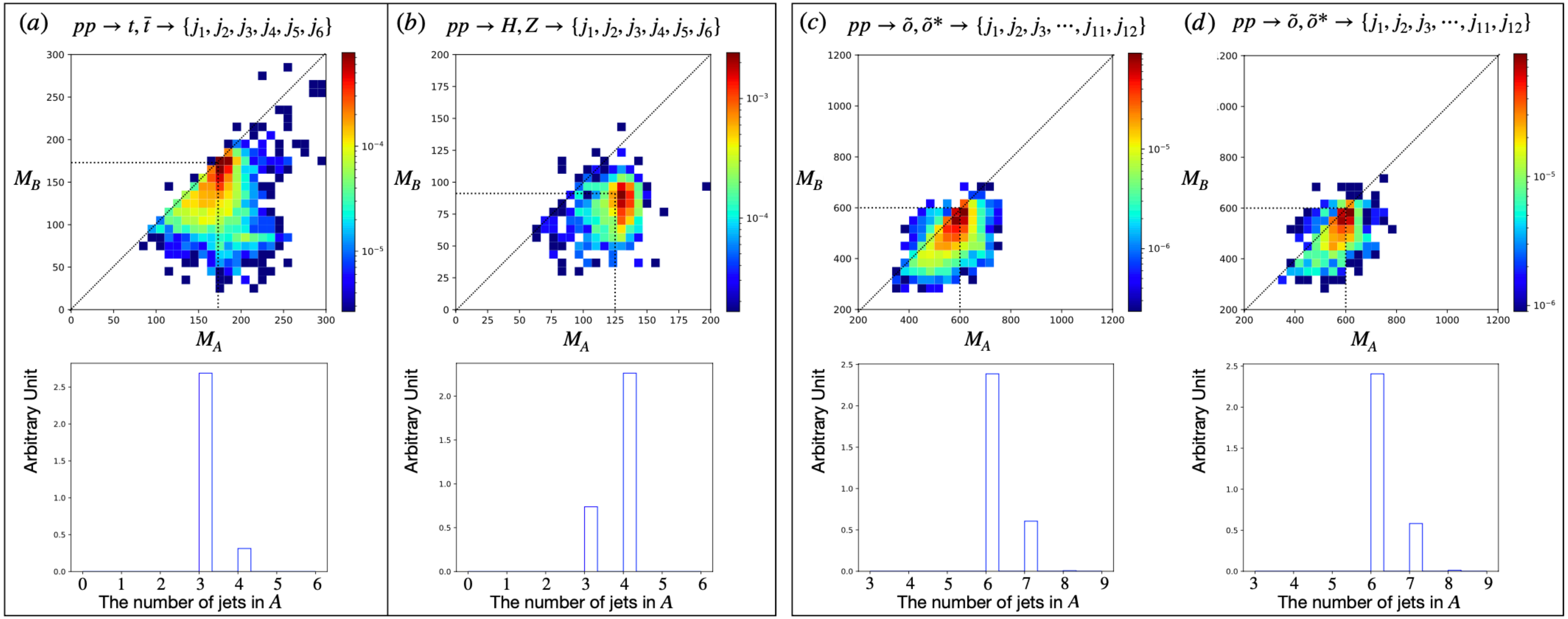
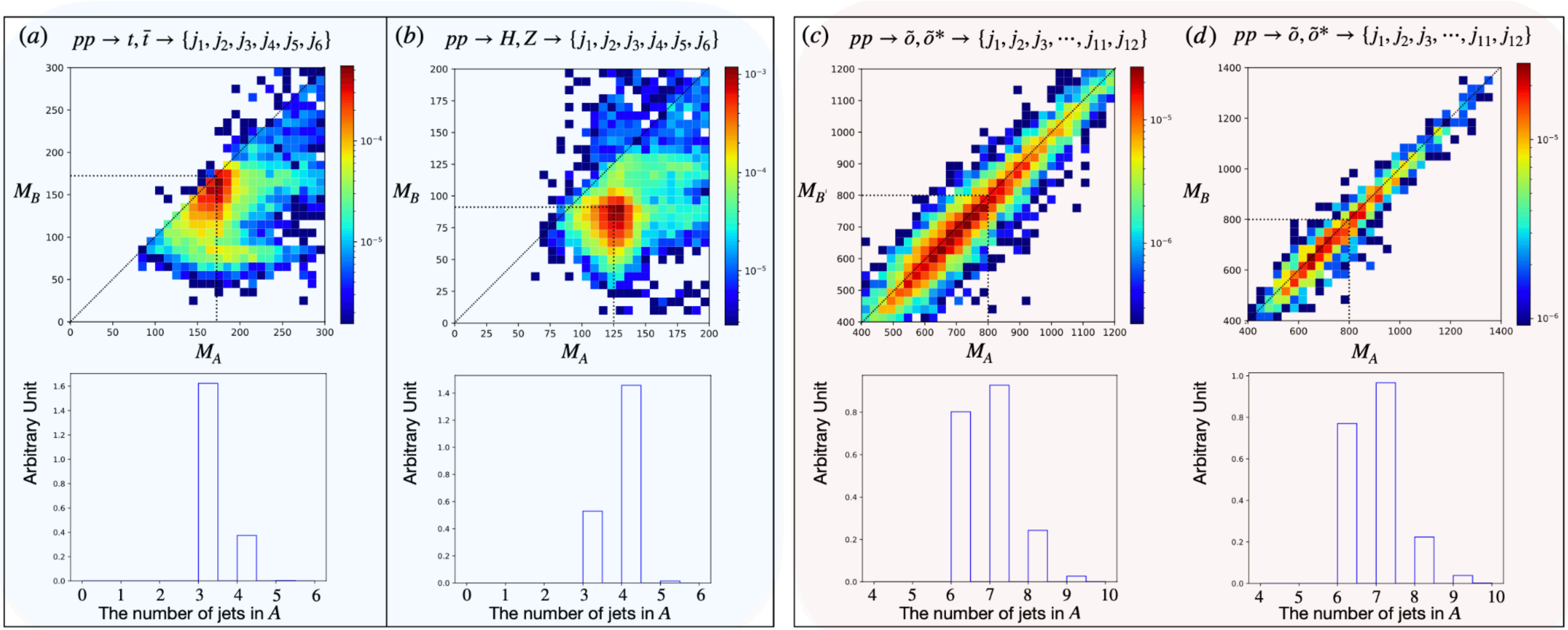


FIG. 3. **Common:** H_{QUBO} is calculated with Monte Carlo samples. To find a global minimum of H_{QUBO}, we use a brute force scanning in (a)-(c), and quantum annealer in (d). For (d), we randomly choose 1000 events from MC samples we used in (c). **Top:** Normalized density histogram for reconstructed mass M_A and M_B **Bottom:** The number of jets clustered into A.

Madgraph → Pythia (ISR/FSR/MPI turned off) → Delphes

Results



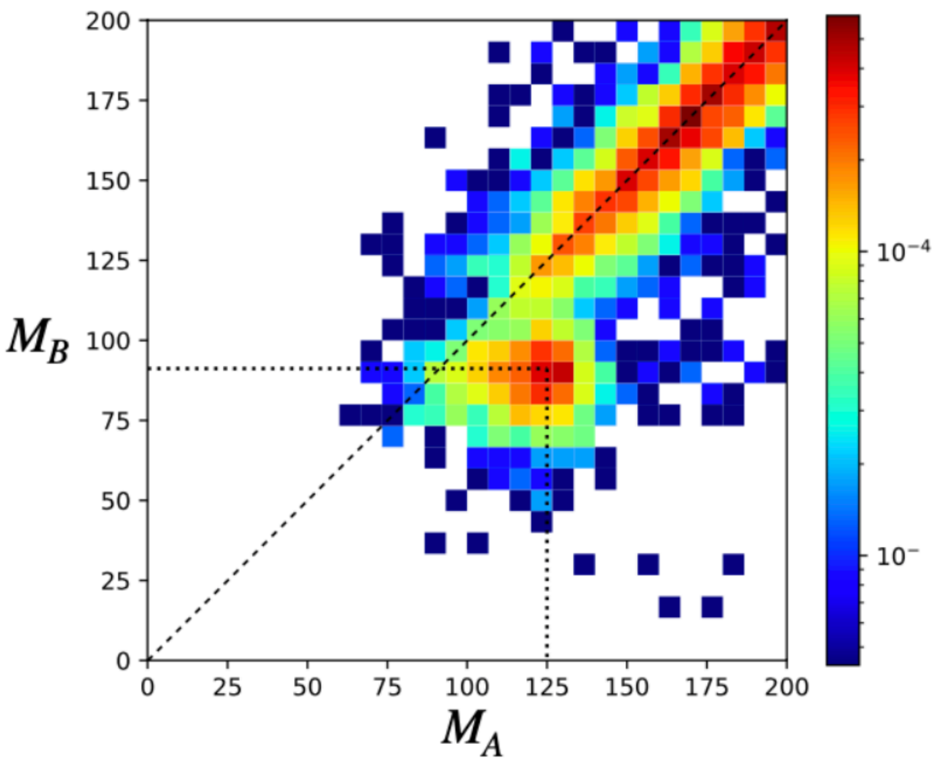
Madgraph → Pythia (**ISR/FSR/MPI turned ON**) → Delphes

Role of the λ term

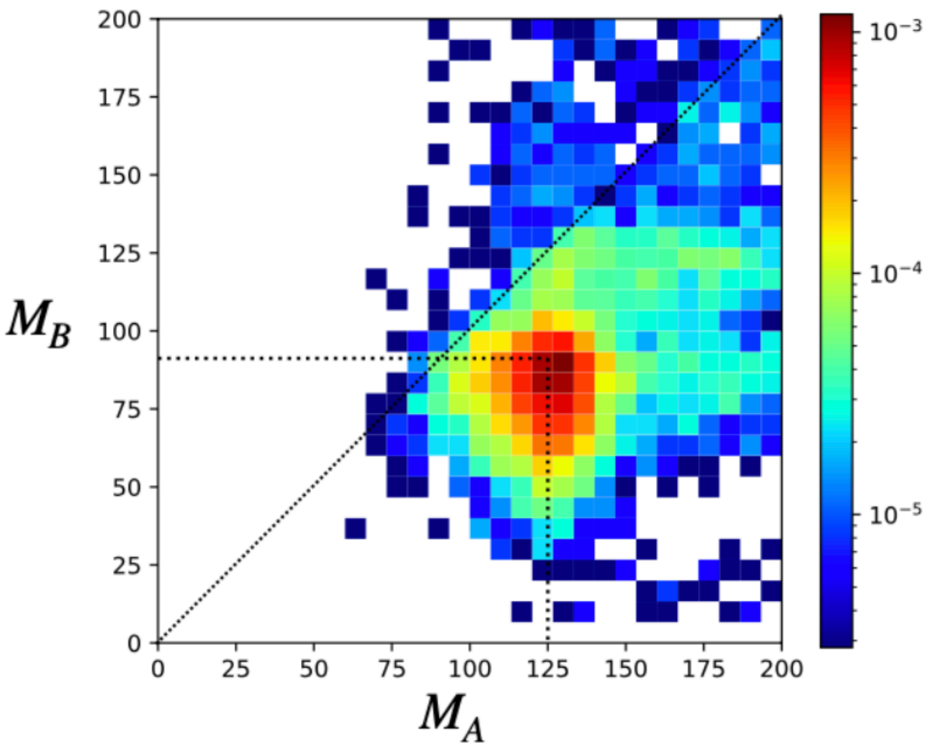
$$H = \left(P_1^2 - P_2^2\right)^2 \rightarrow H + \lambda\left(P_1^2 + P_2^2\right)$$

For different mother particle cases: $pp \rightarrow HZ$

$$H = \left(P_1^2 - P_2^2\right)^2$$



$$H \rightarrow H + \lambda\left(P_1^2 + P_2^2\right)$$



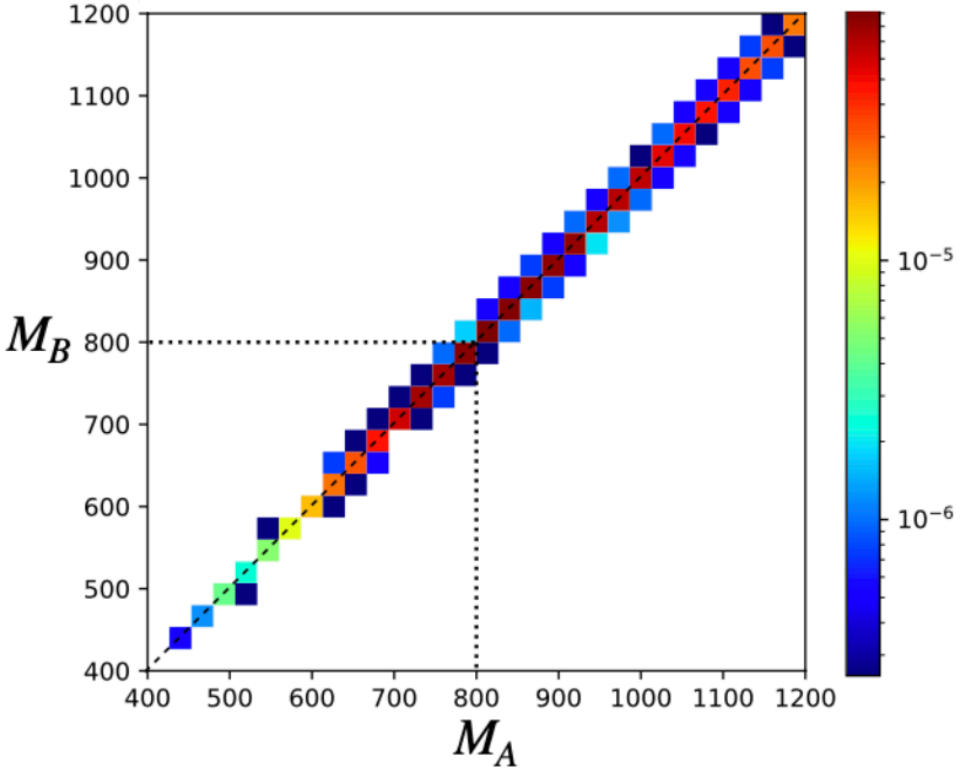
Role of the λ term

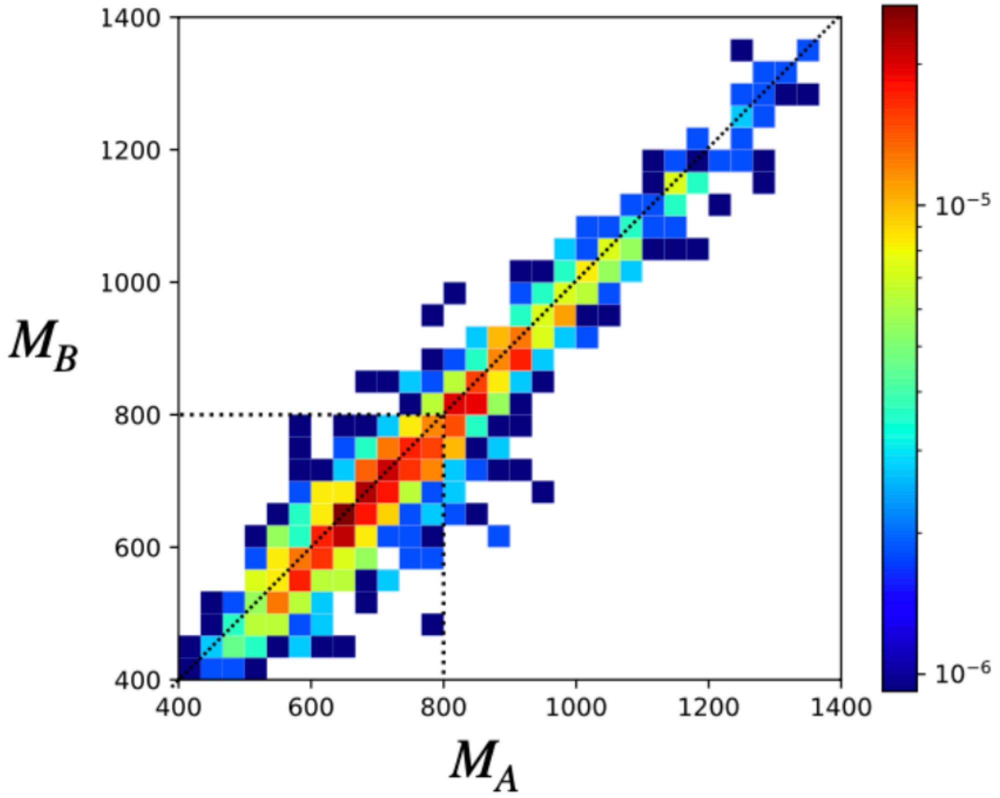
$$H = \left(P_1^2 - P_2^2\right)^2 \rightarrow H + \lambda\left(P_1^2 + P_2^2\right)$$

For smearing effects : $pp \rightarrow \tilde{o}\tilde{o} \rightarrow t\bar{t}t\bar{t}$

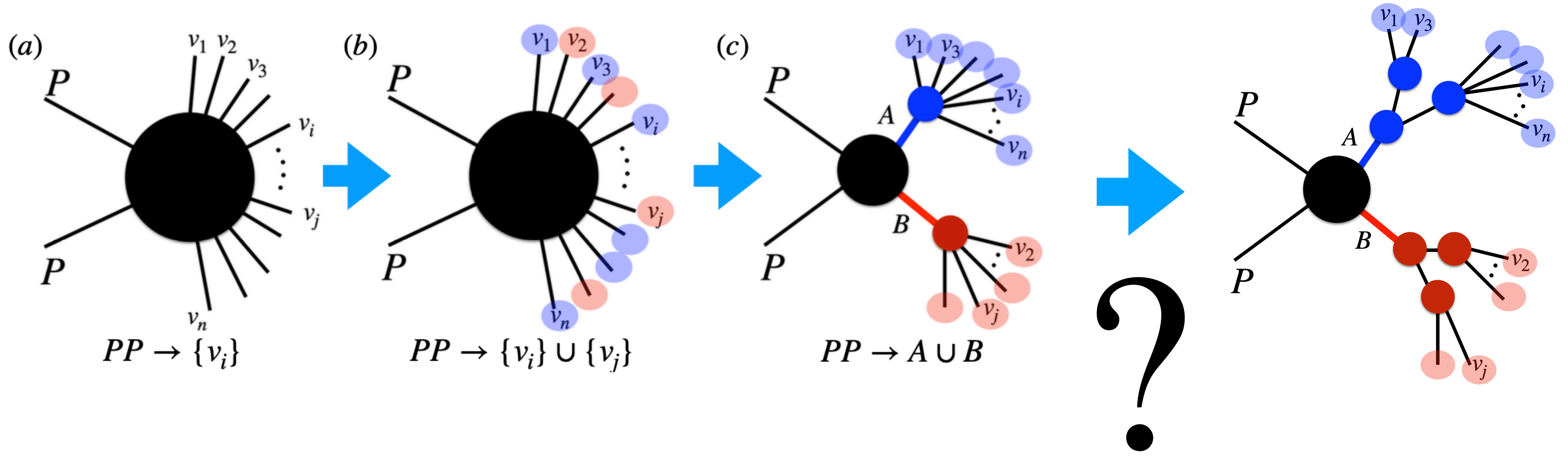
$$H = \left(P_1^2 - P_2^2\right)^2$$

$$H \rightarrow H + \lambda\left(P_1^2 + P_2^2\right)$$





Sequential algorithm



$$H^{(A)}_{\text{QUBO}} = \sum_{ij=1}^{\ell} J'^{\alpha}_{ij} s^{\alpha}_i s^{\alpha}_j + \sum_{i=1}^{\ell} h'^{\alpha}_i s^{\alpha}_i ,$$

$$H^{(B)}_{\text{QUBO}} = \sum_{ij=1}^{m} J'^{\beta}_{ij} s^{\beta}_i s^{\beta}_j + \sum_{i=1}^{m} h'^{\beta}_i s^{\beta}_i ,$$

- For 12 hard-jets production, it would be worthy if we can check whether this is four-tops events or not !

Results

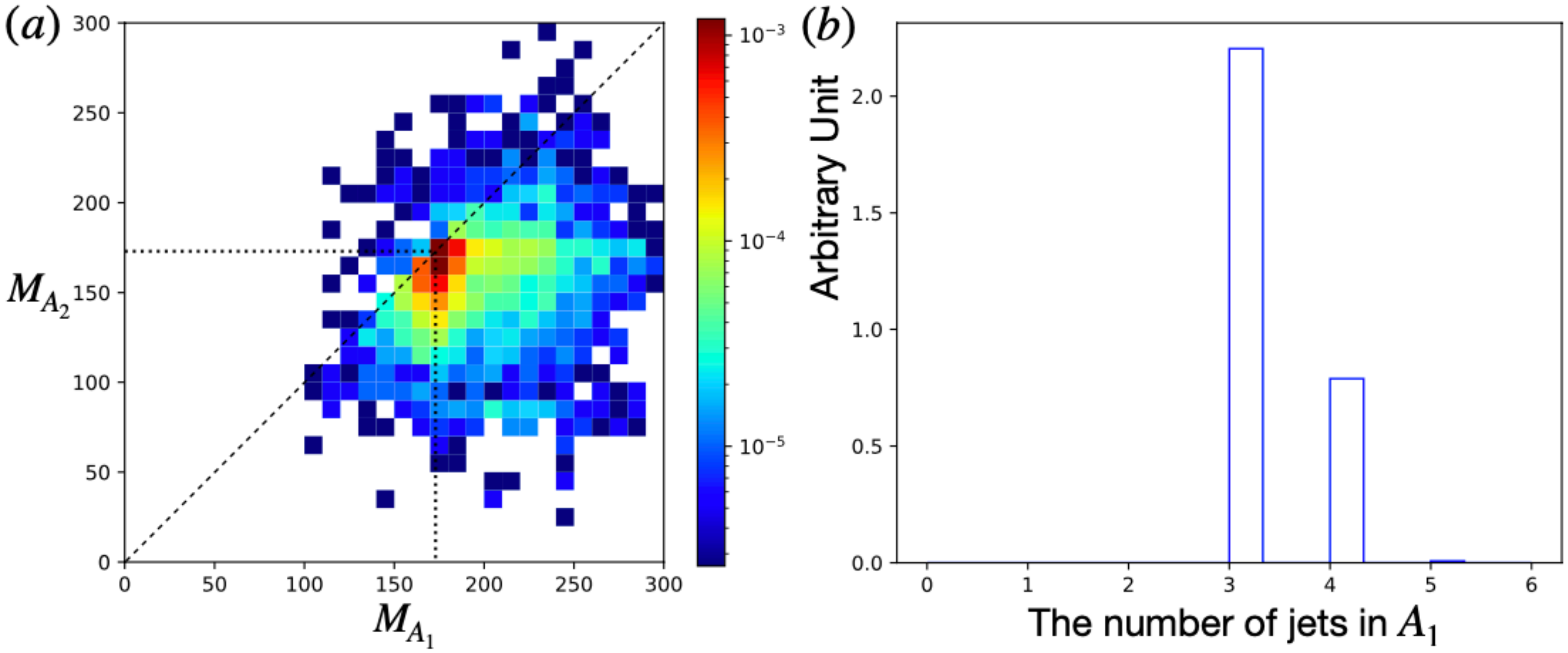


FIG. 4. Sequential application of H_{QUBO} to zoom in on the structure of A in Eq. (7c). After 12 jets are divided into two groups A and B, H_{QUBO} further investigates the structure of A. It identifies that $A \to t\bar{t}$ by measuring (a) masses and (b) the number of decaying particles of A_1, A_2 for $A \to A_1, A_2$.

Compare with Hemisphere method

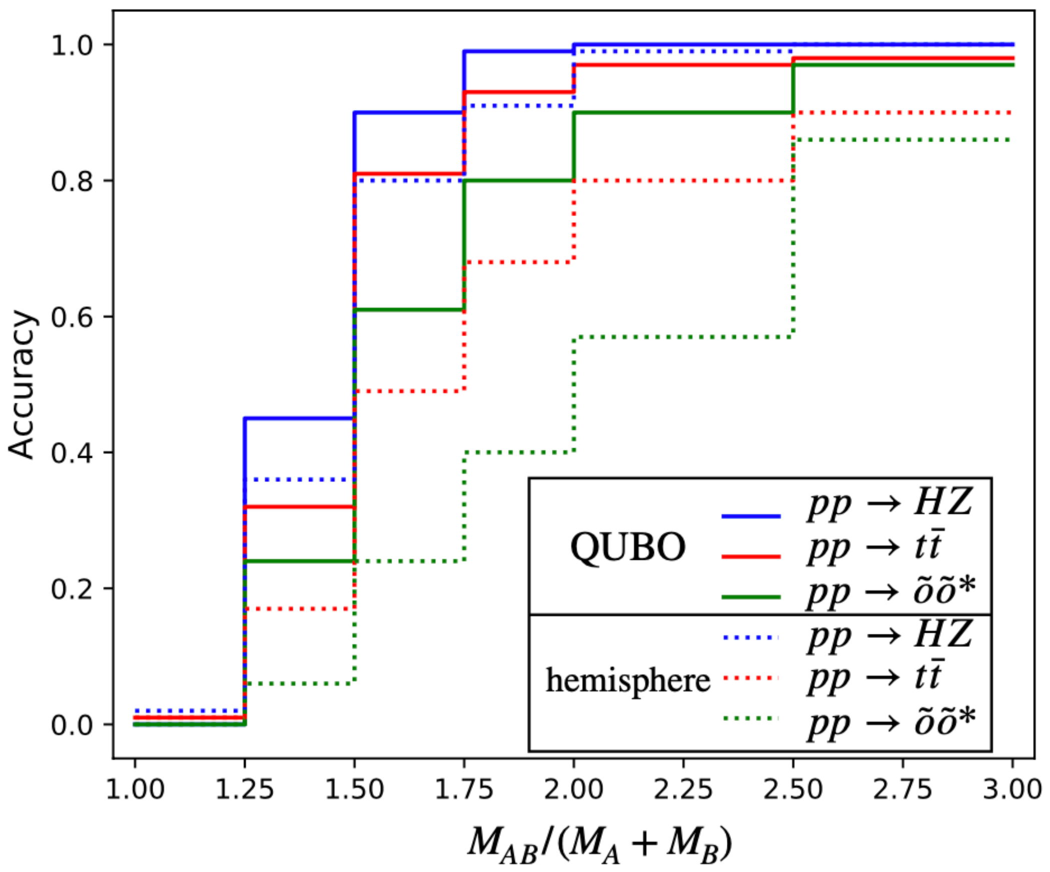


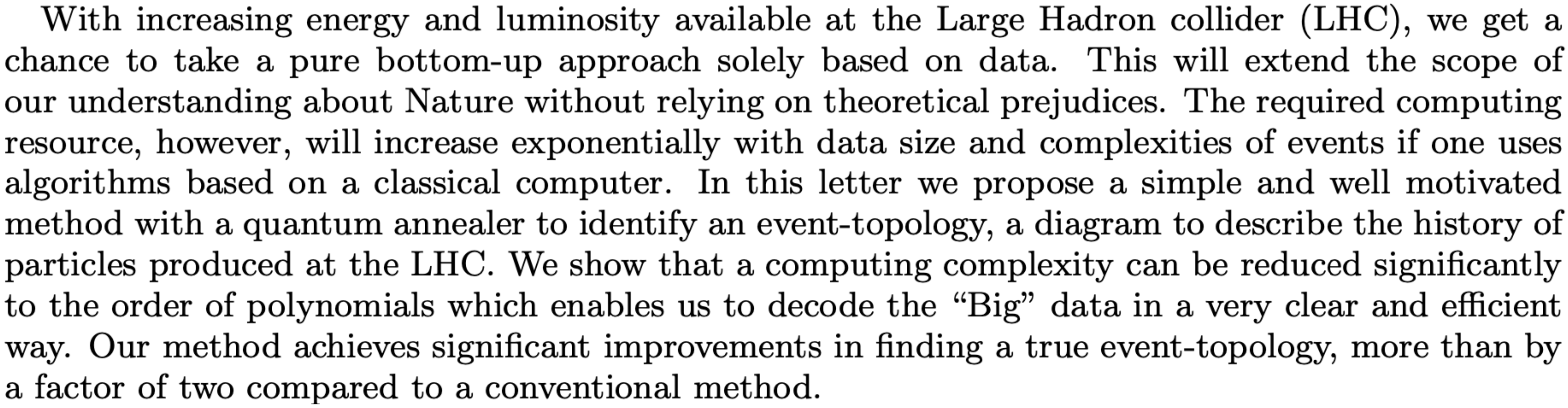
FIG. 6. Matching accuracy same as in Tab. II in terms of their boost factor $M_{AB}/(M_A + M_B)$. Here M_{AB} is an invariant mass of A and B.

Process		$pp \to t\bar{t}$ Eq. (7a)	$pp \to HZ$ Eq. (7b)	$pp \to \tilde{o}\tilde{o}^*$ Eq. (7c)
Algorithm	QUBO	47.3%	89.5%	17.4%
	Hemishere	33.6%	86.2%	7.2%

TABLE II. Matching accuracy for the reconstructed momenta of particles A and B using a clustering algorithm to an actual momenta of A and B (parton level analysis but with same basic cuts as in previous Monte Carlo samples).

Performance of an algorithm based on Hemisphere method becomes weak when particles are **not boosted enough to develop structure**

Conclusion



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Questions for future direction

1. How about 2→ n (n> 2)

2. Off-shell case?

3. Missing daughter particle

4. Contamination from the ISR

5. Systematic error from Quantum Annealer for large qubit

6. Another quantum computing method

7. And more ....