Quantum & Quantum-inspired Optimization for HEP Reconstruction

International Workshop on the High Energy Circular Electron Positron Collider,
November 6-10, 2025

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Picture credits: Qianhui Shi, Yan Liang

2025: 100th Anniversary of QM & Spin

INTERNATIONAL YEAR OF
Quantum Science
and Technology

Werner Heisenberg

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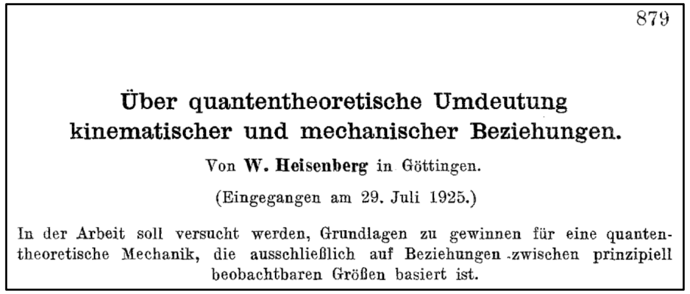
“Quantum-mechanical re-interpretation of kinematic and mechanical relations”
(translation used in “Sources of Quantum Mechanics, edited by B. L. van der Waerden (1967))



879

Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen.

Von W. Heisenberg in Göttingen.

(Eingegangen am 29. Juli 1925.)

In der Arbeit soll versucht werden, Grundlagen zu gewinnen für eine quantentheoretische Mechanik, die ausschließlich auf Beziehungen zwischen prinzipiell beobachtbaren Größen basiert ist.

Z. Physik 33, 879–893 (1925)

https://www.bnl.gov/centuryofspin/

- UNESCO proclaims 2025 as the **International Year of Quantum Science and Technology**, celebrating the **100th anniversary of the initial development of quantum mechanics (i.e. Heisenberg’s paper accepted on 29 July, 1925)**
- It is also the **100th anniversary of spin introduced by Uhlenbeck and Goudsmit**.

2nd Quantum Revolution: A New Era

- **1st quantum revolution:** lasers, transistors, nuclear magnetic resonance, etc.
- **2nd quantum revolution:** Identification and control of a single quantum bit for the first time in human history. **Arrival of commercial quantum computers.**
  - Quantum supremacy for random number generation in 2019/2020.
  - Recent significant speed-up in Willow/Zuchongzhi-3 & surface code implementation → a milestone towards large-scale quantum computers.

Google (2019)

F. Arute et al., Nature 574 (2019) 505

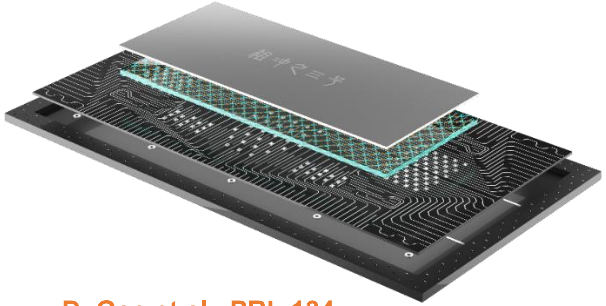
Jiuzhang (九章) (2020)

Science 370 (2020) 1460

Google (2024)

Google AI & collab., Nature 638 (2025) 920

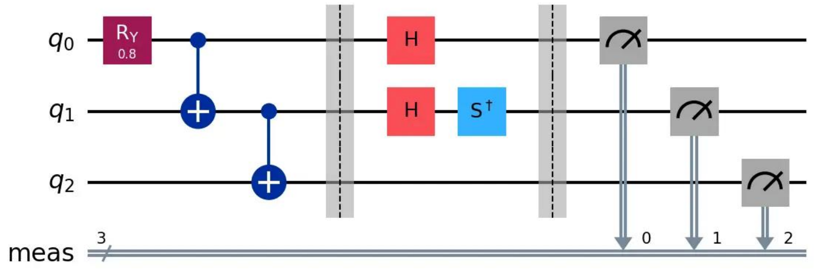
Zuchongzhi-3 (祖冲之3号) (2024)


D. Gao et al., PRL 134 (2025) 090601

Quantum Computing Technologies

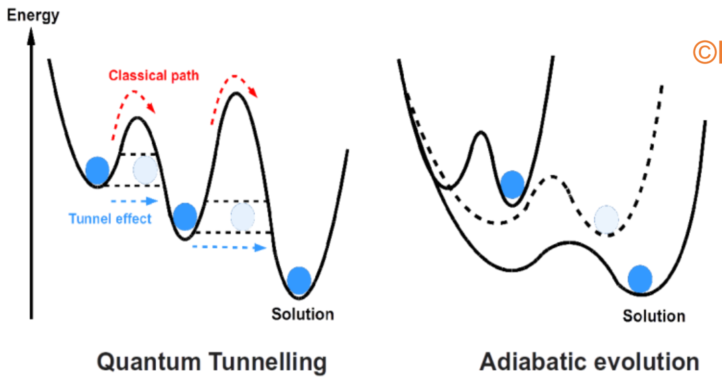
Quantum Gates

- Uses quantum logic gates. Is universal computing.
- **Most quantum computers adopt this approach**



Quantum Annealing

- Uses adiabatic theorem to seek for Hamiltonian ground state.
- Is non-universal, only applicable to optimization problems.



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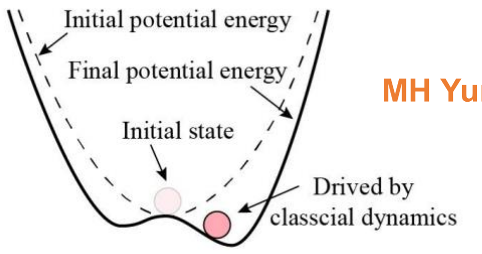
Quantum-inspired

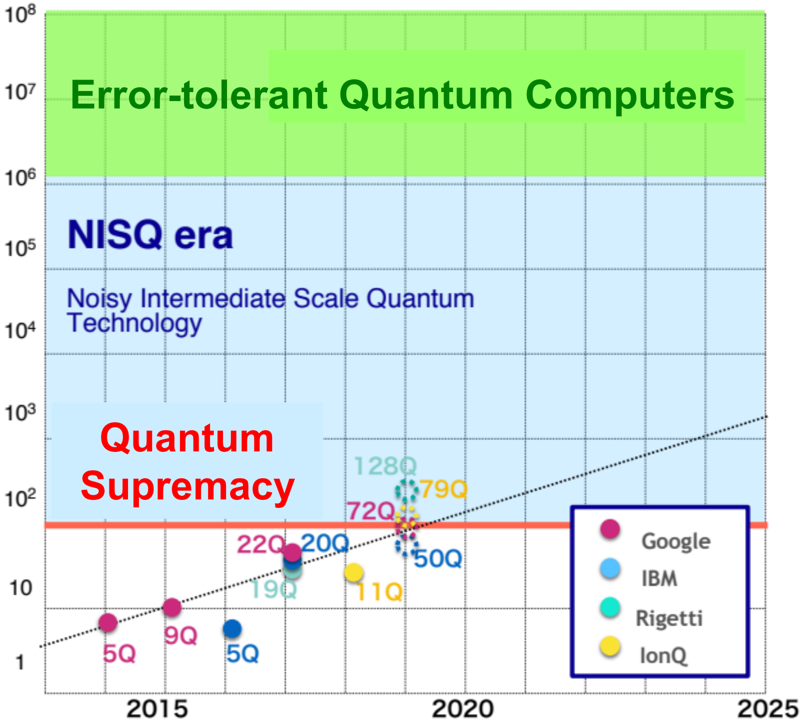
- Classical algorithms: Simulated annealing, simulated coherent Ising machine, simulated bifurcation, tensor network, etc.



Quantum inspired algorithm

MH Yung

Noisy Intermediate Scale Quantum

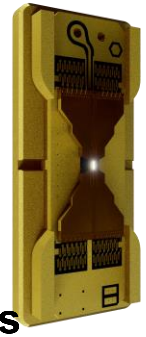


Modified from QunaSys

IBM

Superconductor
Heron 133 qubits

IonQ

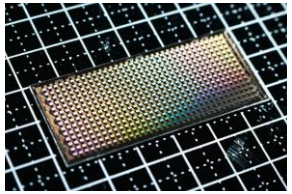


Ion Trap
Forte
32 qubits

QuEra

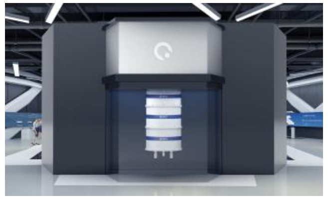
Neutral Atom
Aquila 256 qubits

QuantumCTek



Superconductor
Xiaohong
504 qubits

Origin Quantum



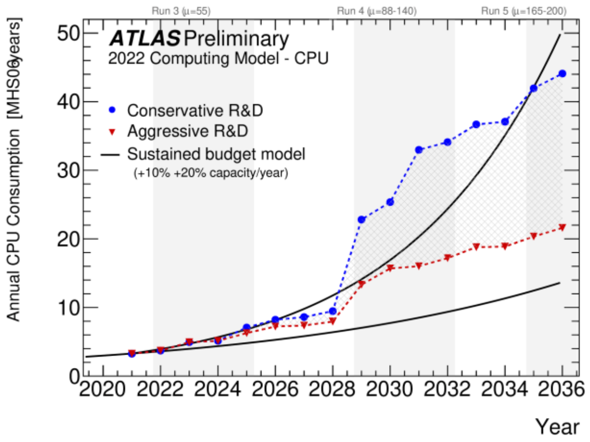
Superconductor
Wukong
72 qubits

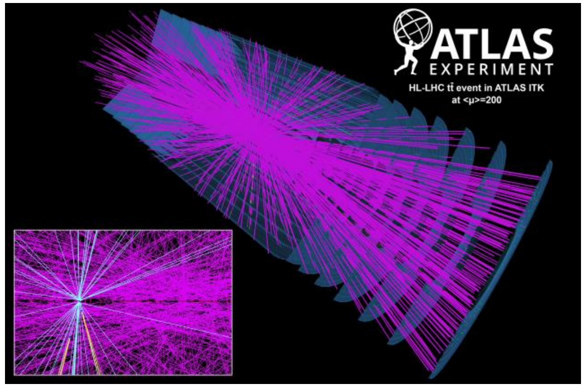
Photons
Jiuzhang-3 255 qubits

- Now is the era of Noisy Intermediate Scale Quantum (NISQ) computers **(>~50 qubits)**。
- **Error mitigation is actively introduced in various hardware. Error-tolerant quantum computers are starting to show up in ion-trap hardware.**

Why Quantum Computing?

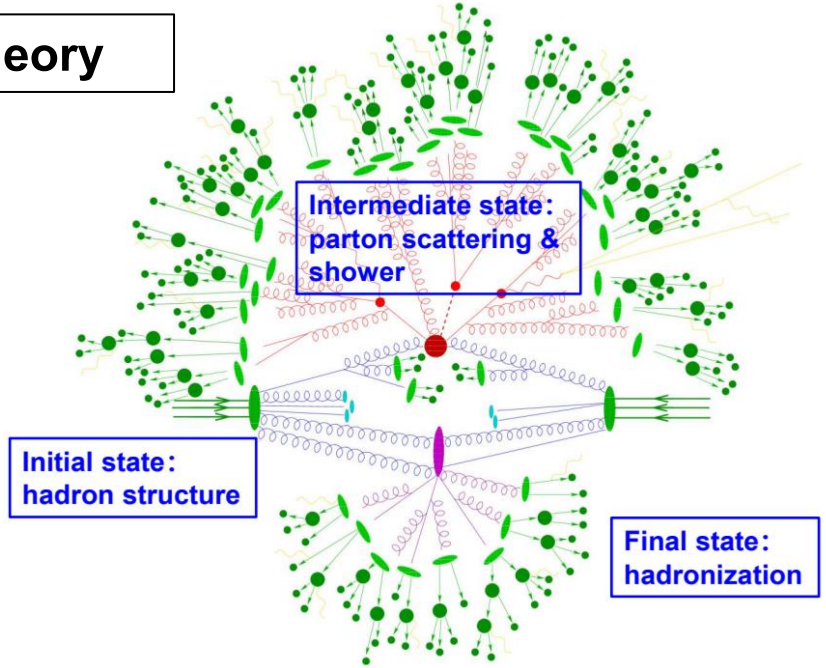
Experiments





- Future colliders (e.g. HL-LHC, CEPC) will enter **the EB era from the current PB-scale operation.**
- At the HL-LHC, annual computing cost will increase by a factor of 10-20. **CEPC Z-pole operation will experience similar challenges.**

Theory



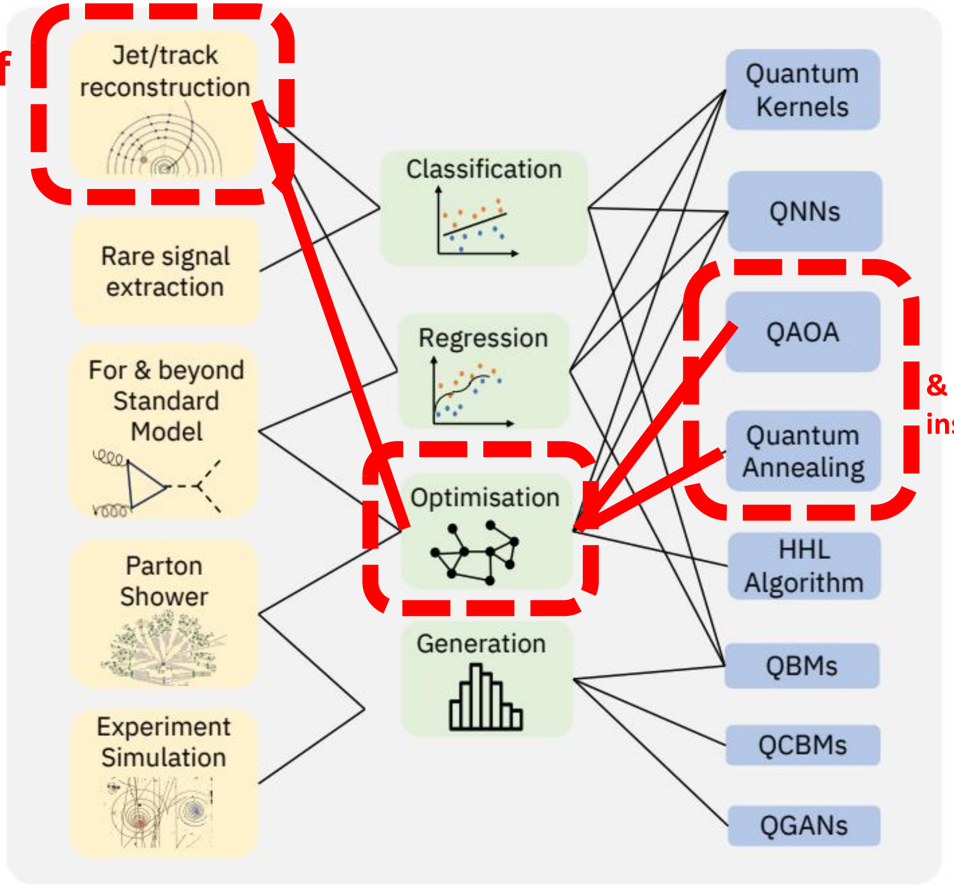
- Strong interaction dynamics is difficult to simulate classically from the first principles.
  - Non-equilibrium, non-perturbative, complexity of many-body quantum systems, quantum interference, sign problem, etc.

Quantum Computing Applications in HEP

A. Di Meglio et al., PRX QUANTUM 5, 037001 (2024)

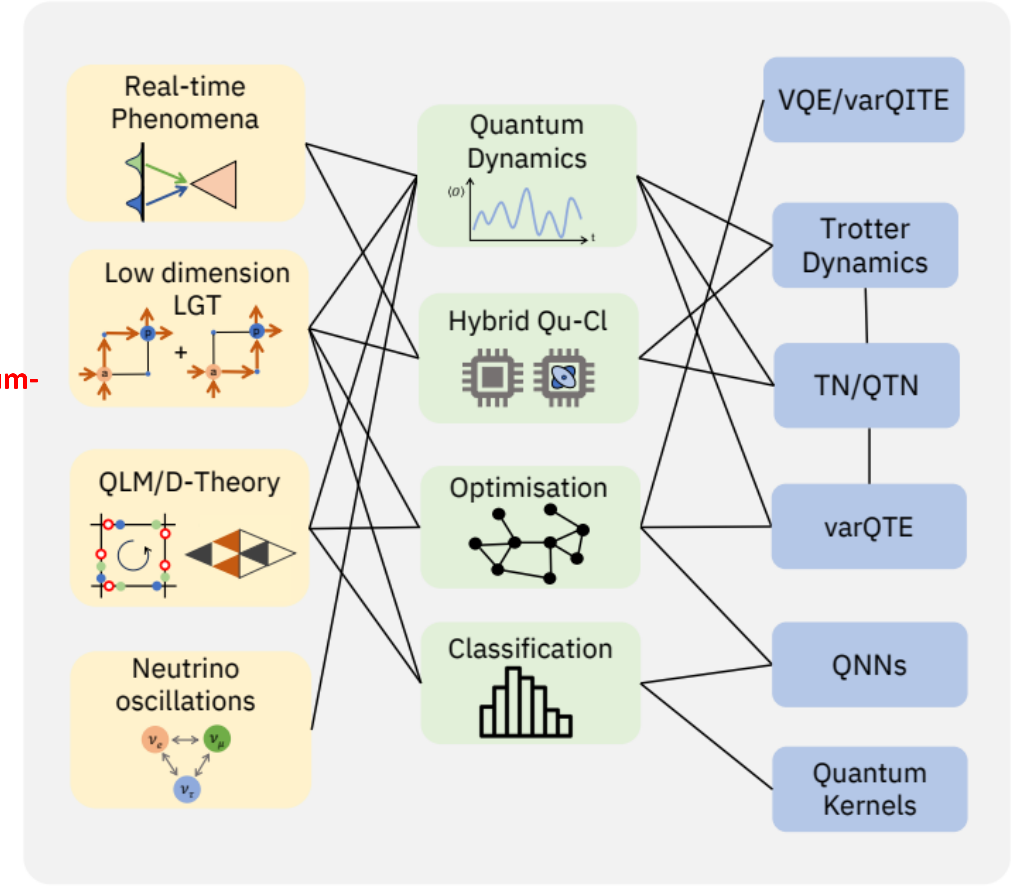
Experiment

Scope of this talk



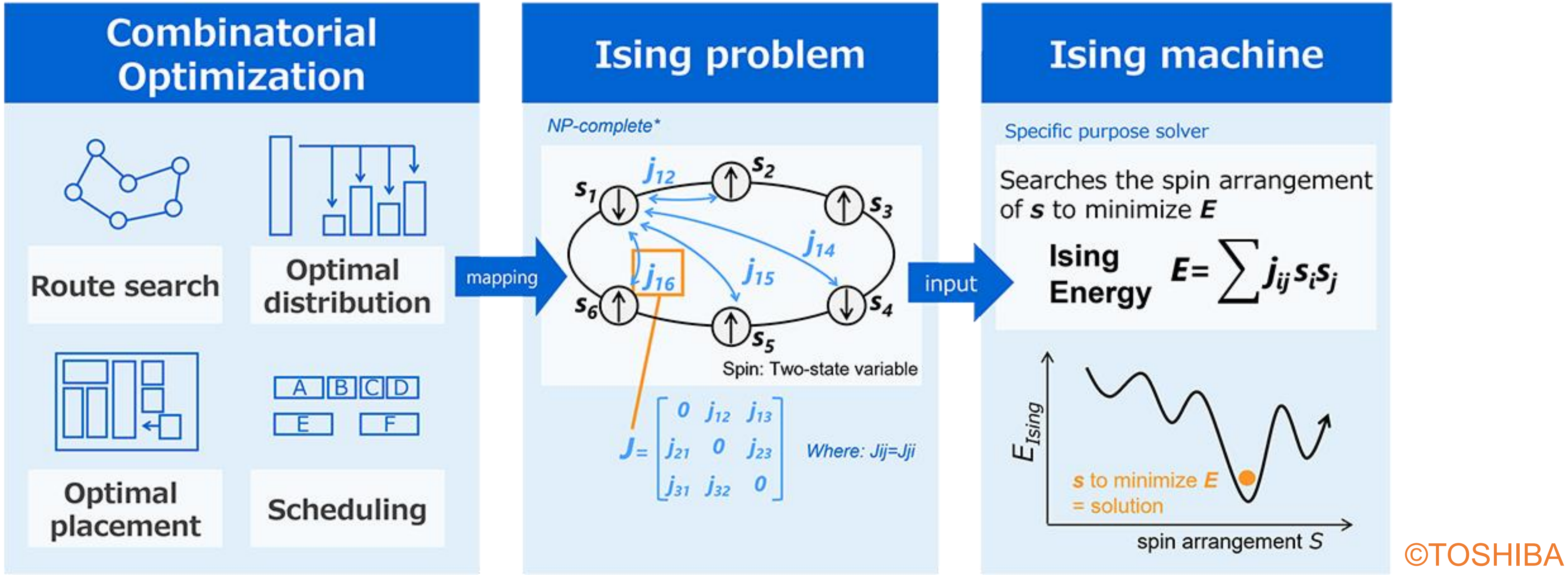
& Quantum-inspired

Theory



About quantum simulation, see also: C.W. Bauer et al., PRX Quantum 4 (2023) 2, 027001

Combinatorial Optimization Problems

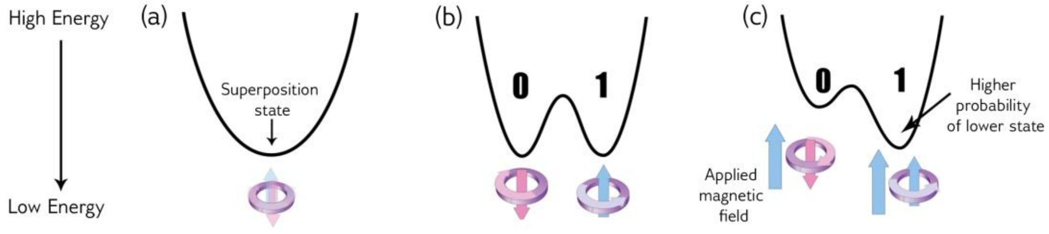


- Practically complicated problems can often be formulated as combinatorial optimization problems/Ising problems → **Ground state of Ising Hamiltonian corresponds to the answer.**
- Non-deterministic Polynomial time
  <u>They are generally NP-complete problem</u>: no efficient algorithm exists to find the solution.
  → But quantum approaches can provide quasi-optimal answers!

Quantum Hardware Solvers

Quantum annealing

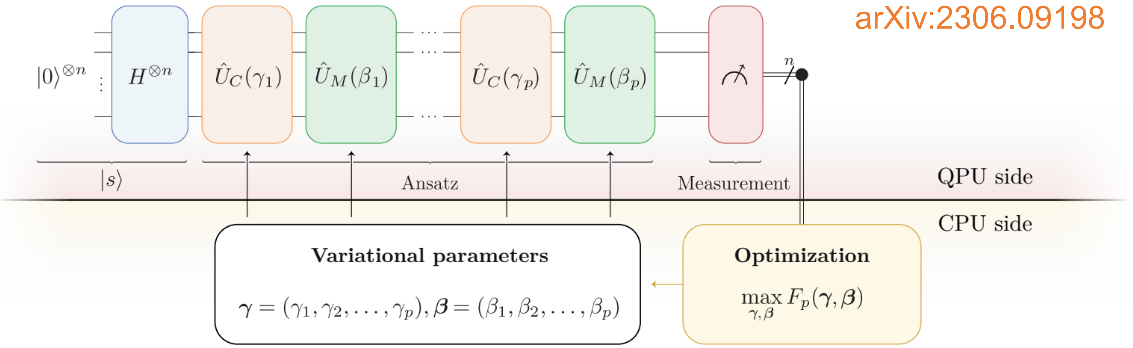
©D-wave



- Quantum annealer looks for the global minimum based on the quantum adiabatic theorem and also uses quantum tunneling.
- Higher number of qubits available than quantum gates (4000+ qubits for D-Wave Advantage2)
- Connectivity among qubits is currently limited (6-ways for 2000Q & 20-ways for D-Wave Advantage2).

Quantum Gates + Classical Hybrid

arXiv:2306.09198

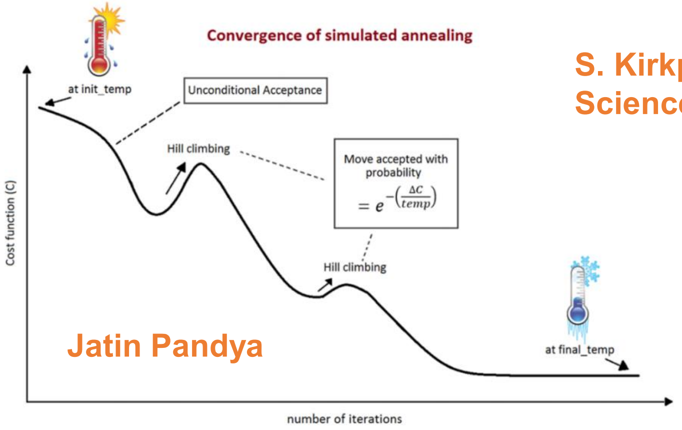


- Quantum gate machines can also solve Ising problems with variational circuits:
  - e.g. **Variational Quantum Eigensolver (VQE), Quantum Approximate Optimization Algorithm (QAOA), imaginary Hamiltonian variational ansatz (iHVA), Imaginary Time Evolution-Mimicking Circuit (ITEMC)** etc.
- Search for the ground state by scanning the variational parameters **with classical optimizers**.

Quantum-Inspired Solvers

"Quantum-inspired" algorithms search for ground state through the classical time evolution of differential equations.

Simulated annealing



S. Kirkpatrick, et al., Science, 220 (1983) 671

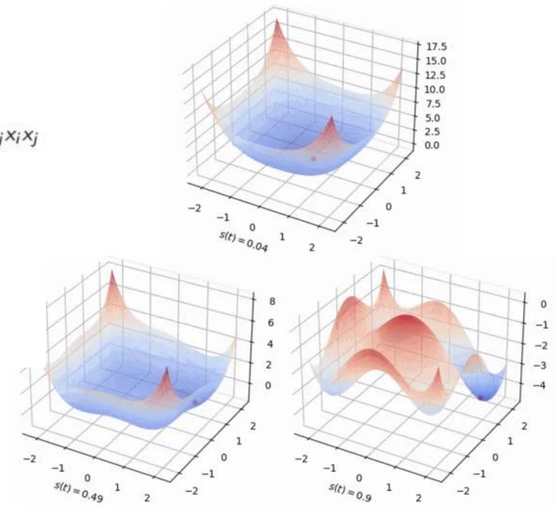
- **Simulated annealing (SA) uses random moves in the solution space.**
- In each random displacement, if lower energy $\Delta E < 0$ is obtained, it is automatically accepted.
- If $\Delta E > 0$, it is accepted probabilistically according to the Boltzmann factor: $P(\Delta E) = \exp(-\Delta E / kT)$.

Simulated bifurcation

$$H_{SB}(x, y, t) = \sum_{i=1}^{N} \frac{\Delta}{2} y_i^2 + \sum_{i=1}^{N} \left[\frac{K}{4} x_i^4 + \frac{\Delta - p(t)}{2} x_i^2\right] - \frac{\xi_0}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} J_{ij} x_i x_j$$

$$\dot{x}_i = \frac{\partial H_{SB}}{\partial y_i} = \Delta y_i$$

$$\dot{y}_i = -\frac{\partial H_{SB}}{\partial x_i} = -\left[K x_i^2 - p(t) + \Delta\right] x_i + \xi_0 \sum_{j=1}^{N} J_{i,j} x_j$$



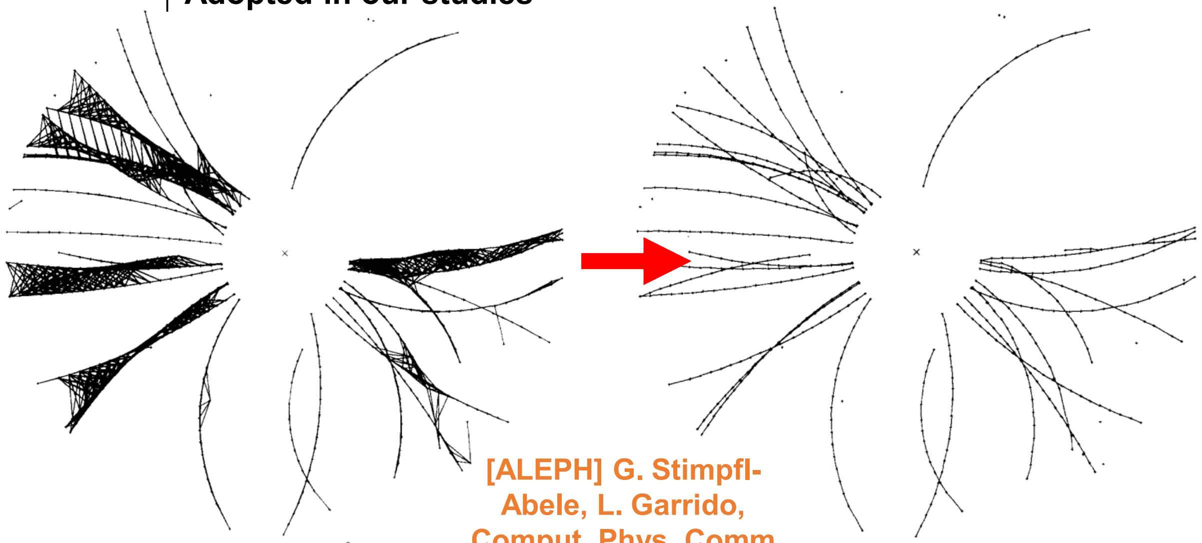
H. Goto et al., Sci. Adv. 2019; 5: eaav2372
H. Goto et al., Sci. Adv. 2021; 7: eabe7953

- **Simulated bifurcation (SB) emulates quantum adiabatic evolution of Kerr-nonlinear parametric oscillators, exhibiting bifurcation phenomena.**
- **Several variants exist** depending on the continuous treatment of the spins (x_i): e.g. **aSB, bSB, dSB**

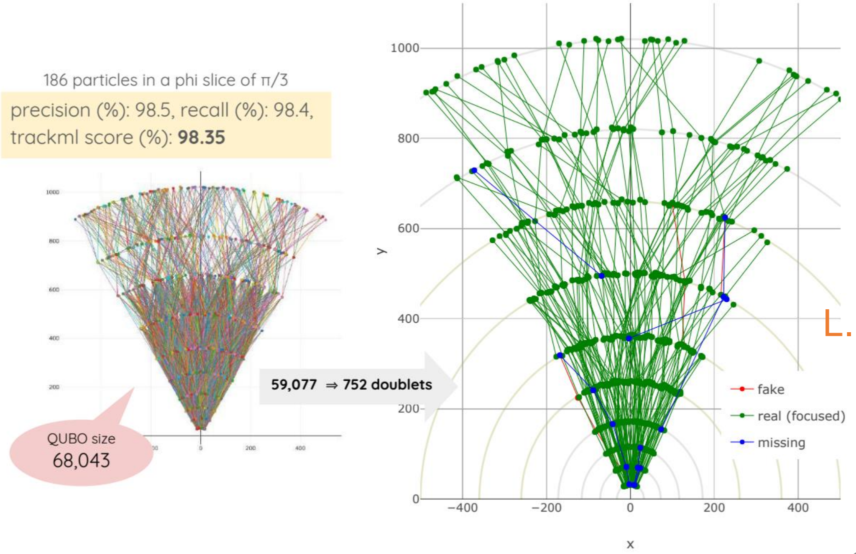
Tracking as Optimization Problem

- **Tracking as an optimization problem: a global approach to reconstruct tracks in one-go.** (↔iterative approach: Combined Kalman Filter)
- **Denby, Peterson (1988, 1989):** formulated track reconstruction as an optimization problem to be solved with neural network & cellular automata. This approach was applied to ALEPH (1991), ARES (1994), ALICE (2004) & LHCb muon system (2008).
- **Modern quantum computing versions:** quantum annealers w/ doublets (A. Zlokapa et al.) & **triplet-based** (F. Bapst et al.) approaches; quantum gate machines (L. Funcke et al., etc.)

↑ **Adopted in our studies**



[ALEPH] G. Stimpfl-Abele, L. Garrido, Comput. Phys. Comm. 64(1), 46–56 (1991)



L. Linder

Track Finding as Ising/QUBO Problem

- Doublets/triplets are connected to reconstruct tracks & it can be regarded as a **quadratic unconstrained binary optimization (QUBO)/Ising** problem.
- **In our study, we adopted a triplet-based QUBO formulation.**

$$O(a,b,T) = \sum_{i=1}^{N} a_i T_i + \sum_{i}^{N} \sum_{j<i}^{N} b_{ij} T_i T_j$$

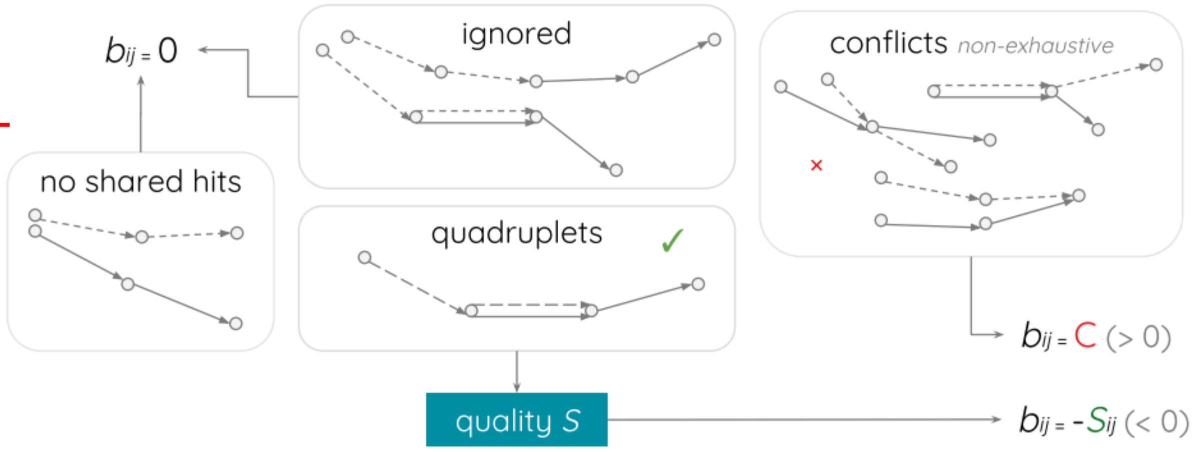
Quality of triplets — Compatibility b/w triplet pairs

$$a_i = \alpha \left(1 - e^{\frac{|d_0|}{\gamma}}\right) + \beta \left(1 - e^{\frac{|z_0|}{\lambda}}\right),$$

b_{ij} = 0 (if no shared hit), 1 (if conflict)
= $-S_{ij}$ (if two hits are shared)

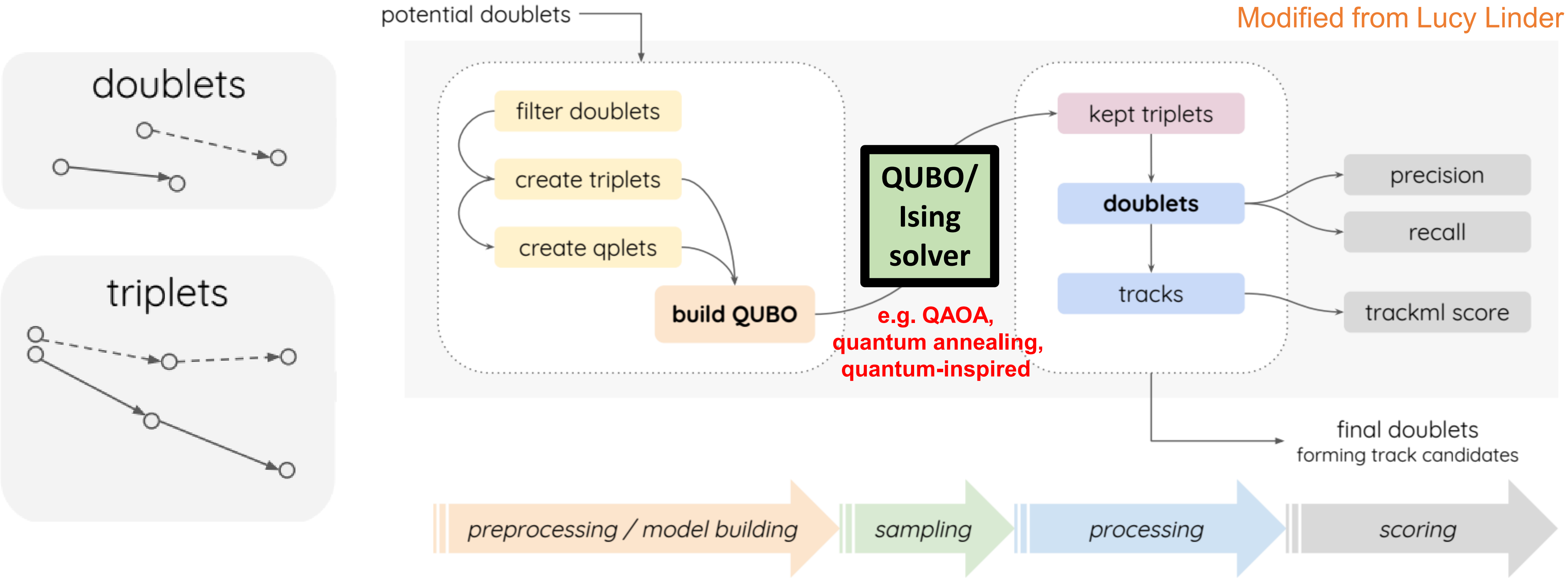
$$S_{ij} = \frac{1 - \frac{1}{2}(|\delta(q/p_{Ti}, q/p_{Tj})| + max(\delta\theta_i, \delta\theta_j))}{(1 + H_i + H_j)^2},$$

F. Bapst et al. Comp. Soft. Big Sci. 4 (2019) 1.



Minimizing QUBO is equivalent to searching for the ground state of the Hamiltonian.

Track Finding Workflow w/ QUBO



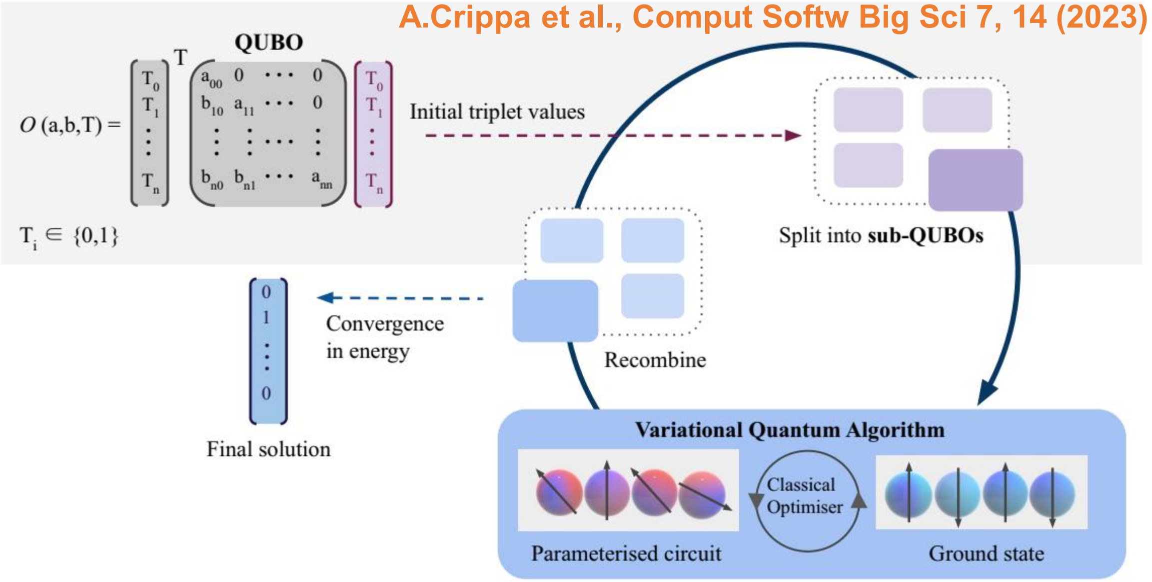
- We build QUBO on an event-by-event basis from the silicon detector hits.
- Predicted ground state will define which triplets should be kept (binary=1). Connecting the adopted triplets will give us the tracks.

H. Okawa, Springer CCIS, 2036 (2024) 272–283, arXiv:2310.10255

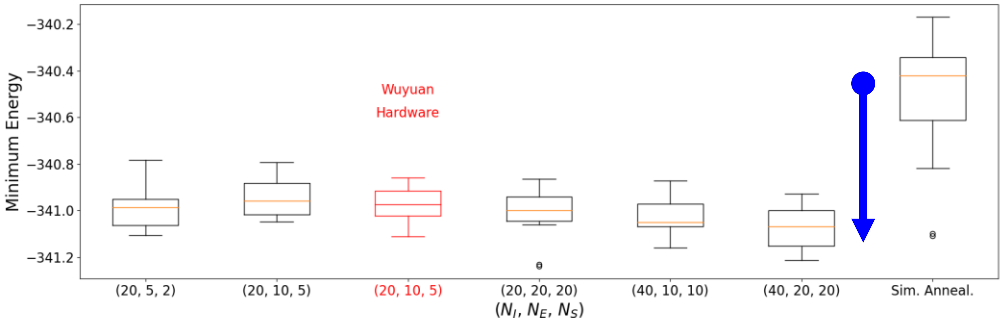
Quantum Hardware Approaches

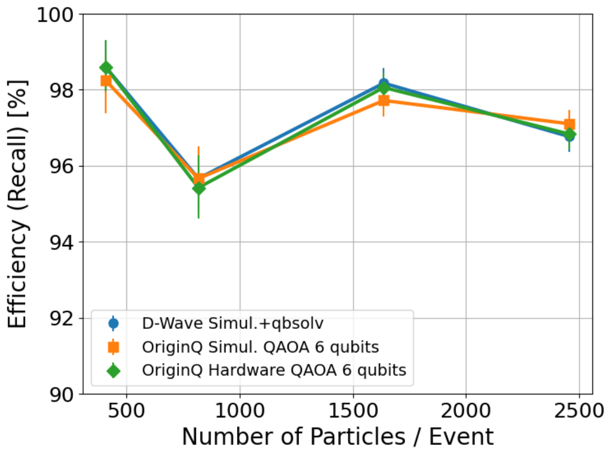
- # of triplet candidates determines # of qubits required → **HL-LHC conditions (~O(0.1M) qubits) do not fit into the current scale of quantum annealing & gate computers**
- **QUBO is split into sub-QUBOs.** There is no visible degradation in Ising solving precision, but **the computation speed degrades by a few orders of magnitude**.

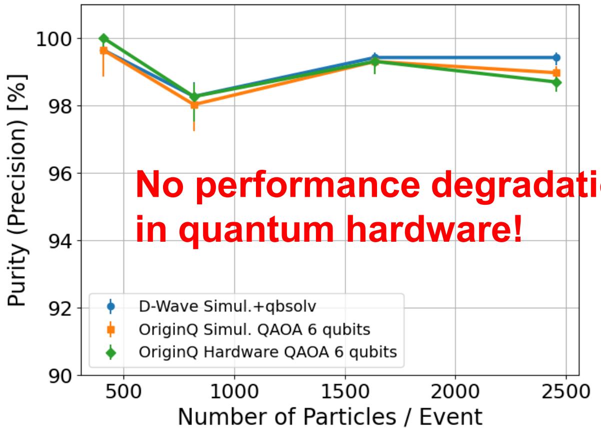
A.Crippa et al., Comput Softw Big Sci 7, 14 (2023)



Using theoretically robust sub-QUBO algorithm (Multiple Solution Instances)

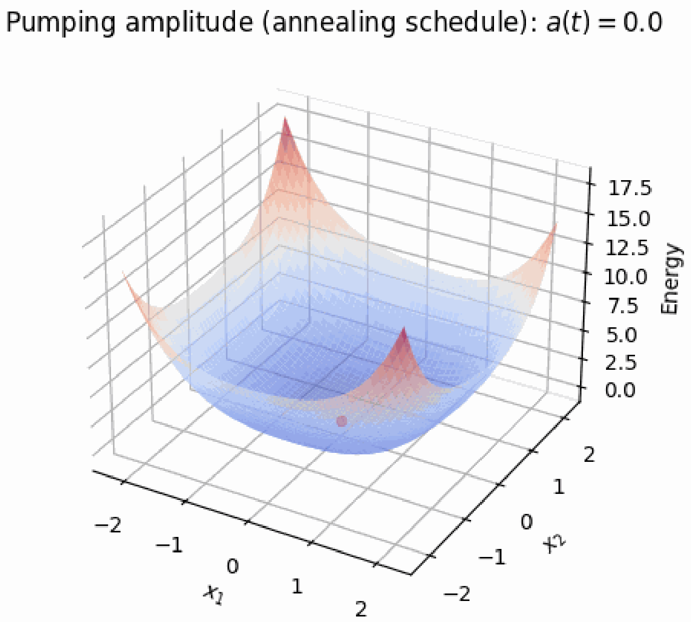


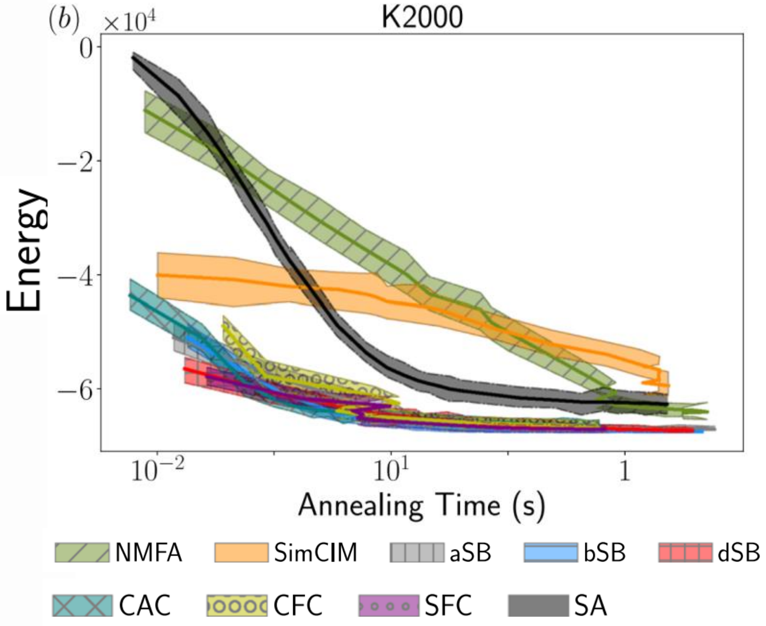




No performance degradation in quantum hardware!

Quantum-Inspired Approach (SB)





Graph size	Algorithm	Hardware	Time(s)
	TTN	CPU 1 core	5.62
	Brute-force search[46]	GPU Titan V	$>10^{48}$
$4 \times 4 \times 8$	Exact belief propagation[13]	CPU 1 core	~0.96
	QA[13]	D-Wave	~0.05
	bSB	CPU 1 core	0.12
	bSB	GPU Tesla V100	<0.001
	TTN	CPU 1 core	32400
	TTN[44]	GPU Tesla V100	84
$8 \times 8 \times 8$	Brute-force search[46]	GPU Titan V	$>10^{190}$
	Exact belief propagation[13]	CPU 1 core	~2880
	dSB	CPU 1 core	17.64
	dSB	GPU Tesla V100	<0.68

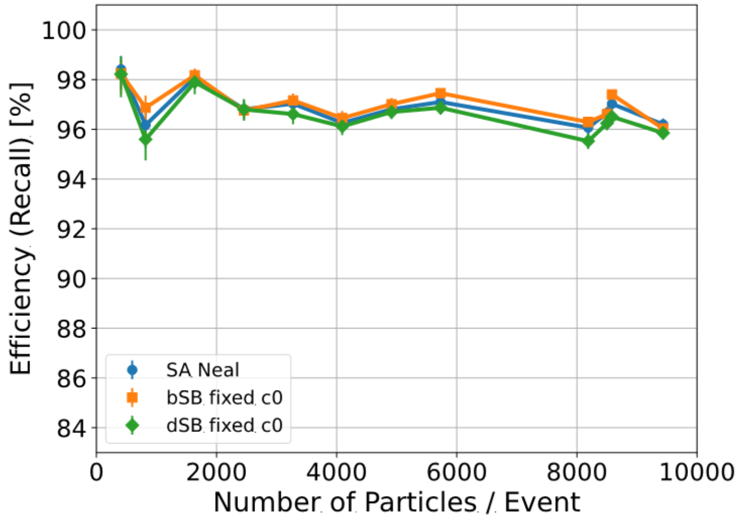
Q.G. Zeng et al., Comm. Phys. (2024) 7:249

- **SB is a powerful quantum-inspired algorithm & can directly handle million-qubit-level problems.**
- **It can run in parallel** unlike simulated annealing. It also benefits from **GPUs & FPGAs**.
- **It is known to outperform other classical algorithms & quantum annealing (QA) for some existing problems: both in terms of minimum energy prediction & computing speed.**

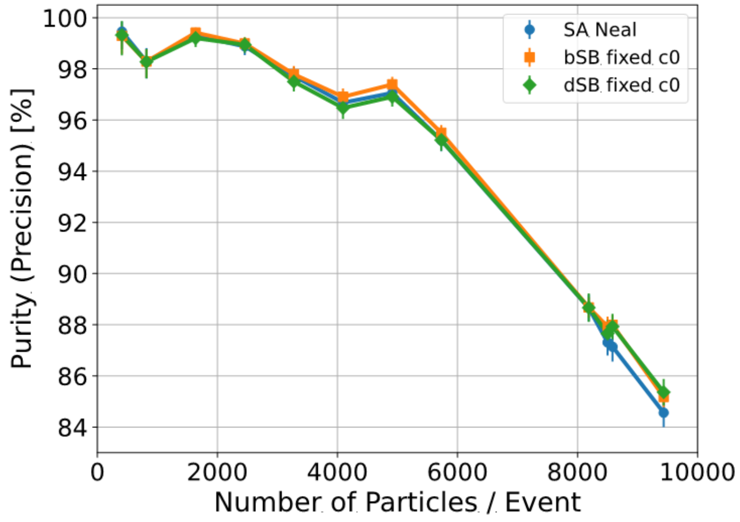
H. Okawa, Q.G. Zeng, X.Z. Tao, M.H. Yung, Springer Comput. Softw. Big Sci. 8, 16 (2024)

Quantum-Inspired Track Finding

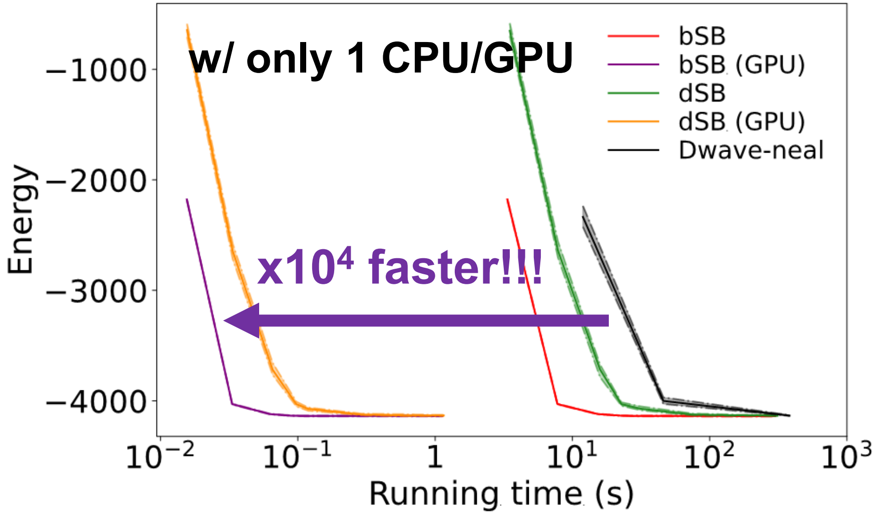
Efficiency



Purity



Ising Energy vs computing time



- **Quantum-annealing-inspired algorithm can DIRECTLY handle the HL-LHC dataset.**
- SB provides compatible or slightly better efficiency & purity than D-Wave Neal SA.
- bSB provides **4 orders of magnitude speed-up (23min → 0.14s) from D-Wave Neal** for HL-LHC data **(cf. D-Wave hardware w/ qbsolv is ~2 orders of magnitude slower than Neal).**
- **SB can effectively run w/ multiple processing, GPU & FPGA → Perfect match with HEP!!**

Multiple Jet Clustering as Optimization

QUBO Formulation

$$O_{\mathrm{QUBO}}^{\mathrm{multijet}}(x_i) = \sum_{n=1}^{n_{\mathrm{jet}}} \sum_{i,j=1}^{N_{\mathrm{input}}} Q_{ij} x_i^{(n)} x_j^{(n)} + \lambda \sum_{i=1}^{N_{\mathrm{input}}} \left(1 - \sum_{n=1}^{n_{\mathrm{jet}}} x_i^{(n)}\right)^2 ,$$

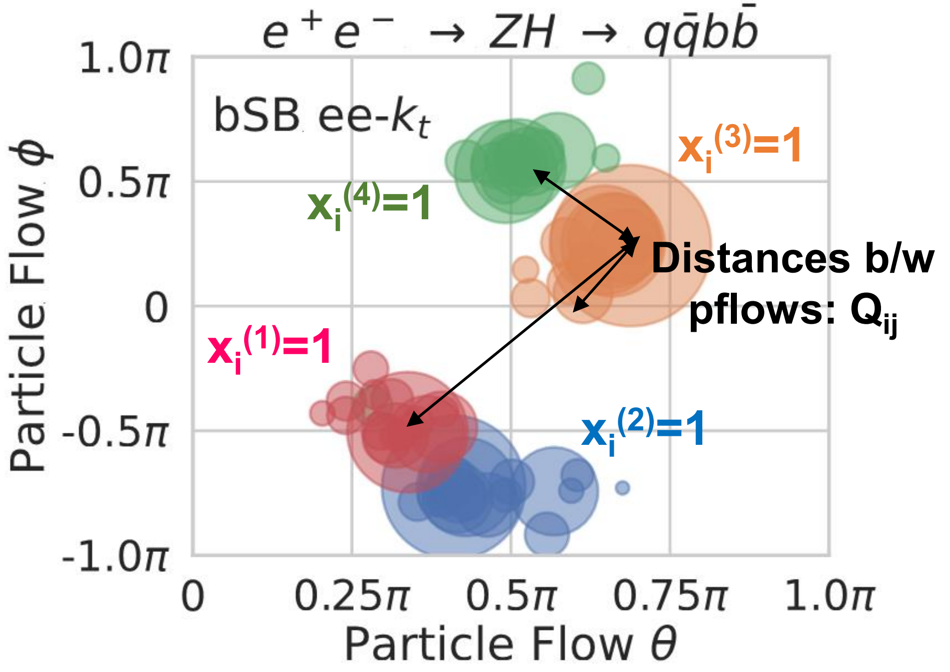
Defines distances b/w particle flow candidates

Avoids double/none-assignment of particle flow candidates

$$Q_{ij} = 2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij}).$$ **[ee-k_t distance]**

$$Q_{ij} = -\frac{1}{2}\cos\theta_{ij}$$ **[angle-based]**

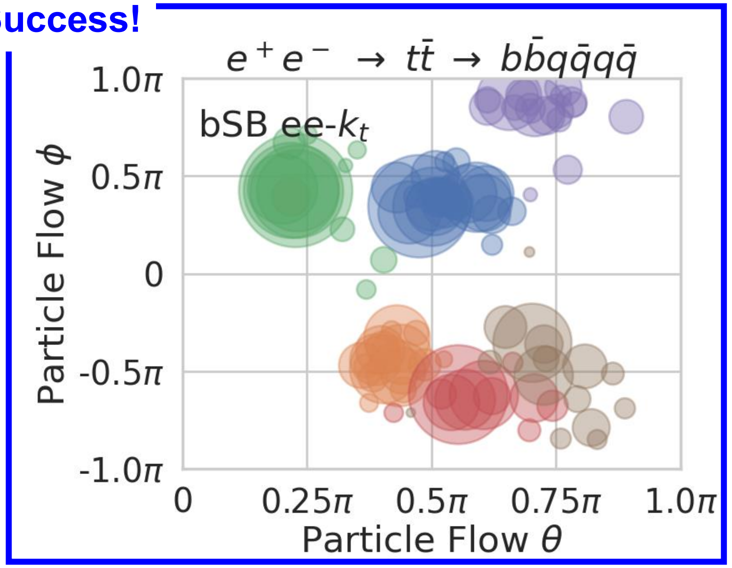
D. Pires, Y. Omar, J. Seixas, PLB 843 (2023) 138000



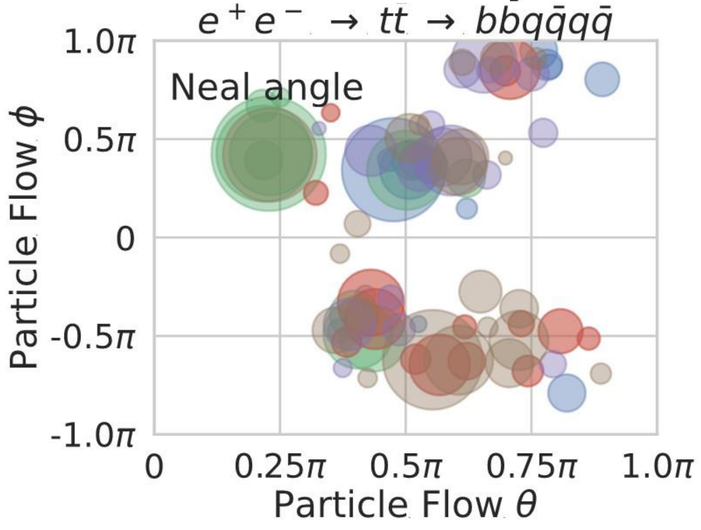
- **Jet clustering can also be formulated as a fully-connected QUBO/Ising problem.**
- **Here, we consider exclusive jet finding (i.e. fixed number of jets):** the baseline at CEPC & other e+e- future Higgs factories.
- **We adopt the ee-k_t distance in QUBO. QUBO is designed for multijet beyond dijet.** $x_i^{(n)}$=1 means i-th particle flow belongs to n-th jet.
  → Performance is compared to the angle-based distance method from a previous study (D. Pires et al.).

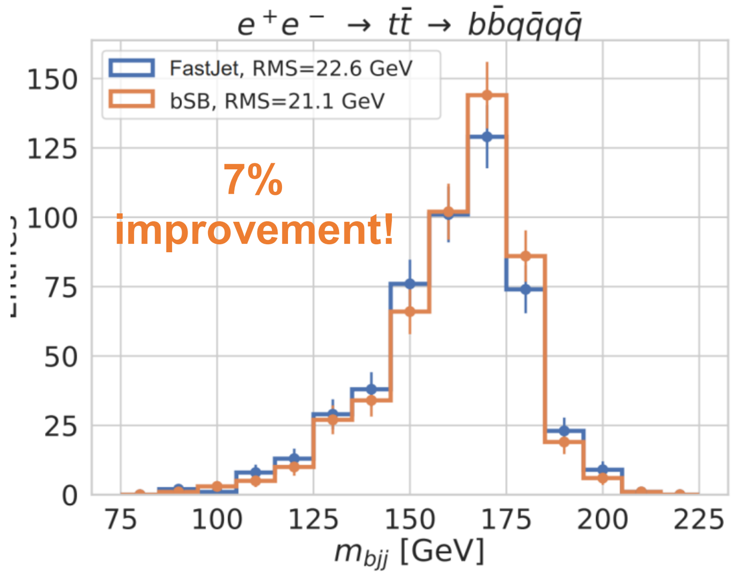
Event Displays ($t\bar{t}$)

Success!



Previous method



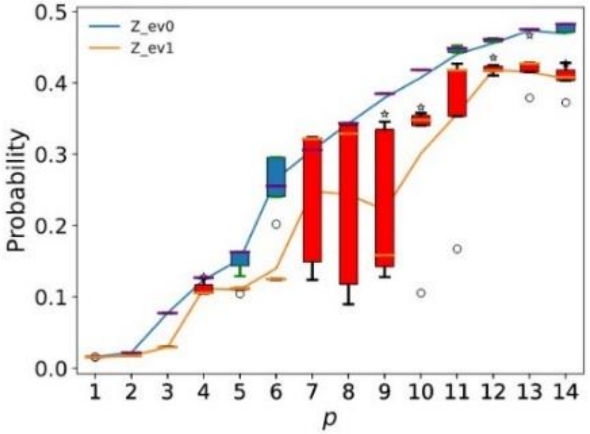


- **Only bSB w/ ee-k_t QUBO model can reasonably reconstruct all jets.** **Angle QUBO model & other quantum-inspired algorithms miss some jets and/or PFlows are totally mixed up.**
- **bSB improve mass resolution for multijet! (6% for H→bb, 7% for top quark→bqq)**
- Other quantum-inspired algorithms (dSB & D-Wave Neal) already has ~20% degradation in Z mass resolution & unable to properly reconstruct jets in multijet events.

Comparison w/ Quantum Hardware

- Performance was compared for two simplified jet datasets (12 qubits) to quantum annealing and QAOA using simulator.
    - [QuantumAnnealing.jl package] is used to evaluate D-Wave 2000Q performance (6-way connectivity).
- Even for such small datasets, **bSB exceeds the speed of quantum annealing by about two orders of magnitude & even more for QAOA** (w/ a caveat that QAOA should run faster on real quantum hardware).

QAOA Performance

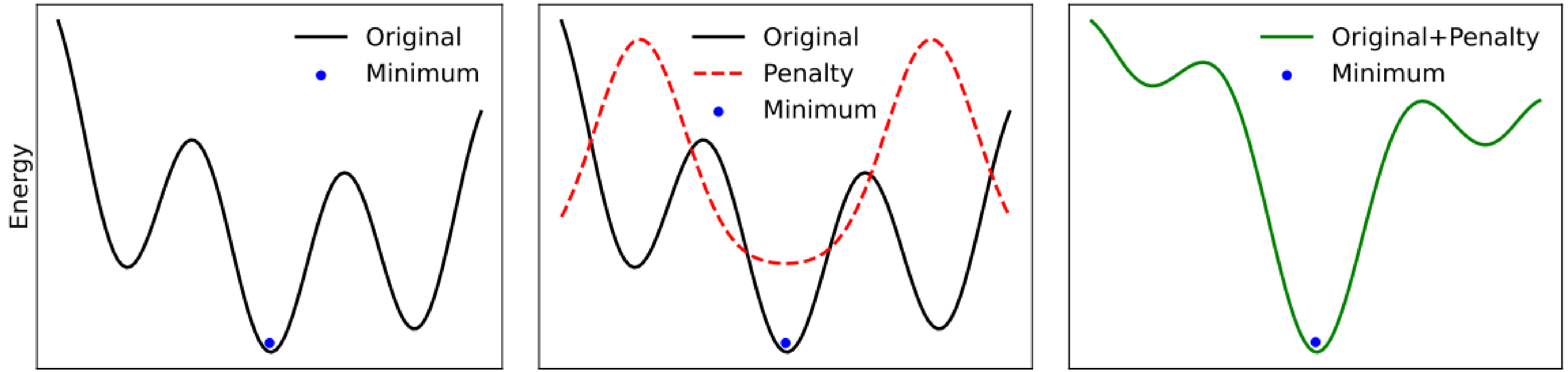


Time-to-solution for D-Wave 2000Q estimated by simulation, bSB, dSB, and QAOA on a quantum circuit simulator for two simplified $Z \to q\bar{q}$ events.

Event	D-Wave [s]	bSB [s]	dSB [s]	QAOA [s]
0	21.29	0.35	0.79	1.07×10^3
1	20.52	0.36	0.89	3.36×10^3

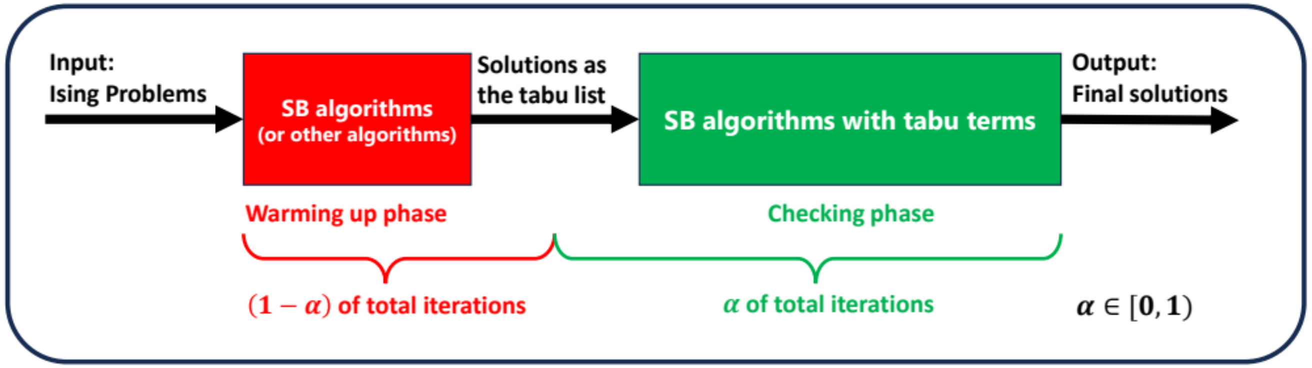
XZ Tao, QG Zeng, ZJ Huang, BW Zuo, J Zhuang, H Okawa, MH Yung, under review

Further Improvement in Quantum-Inspired



- We have developed a new variant of SB: Tabu-enhanced simulated bifurcation.
- **During the warming-up phase, penalty is applied to local minima extracted.**

Tabu-Enhanced Simulated Bifurcation

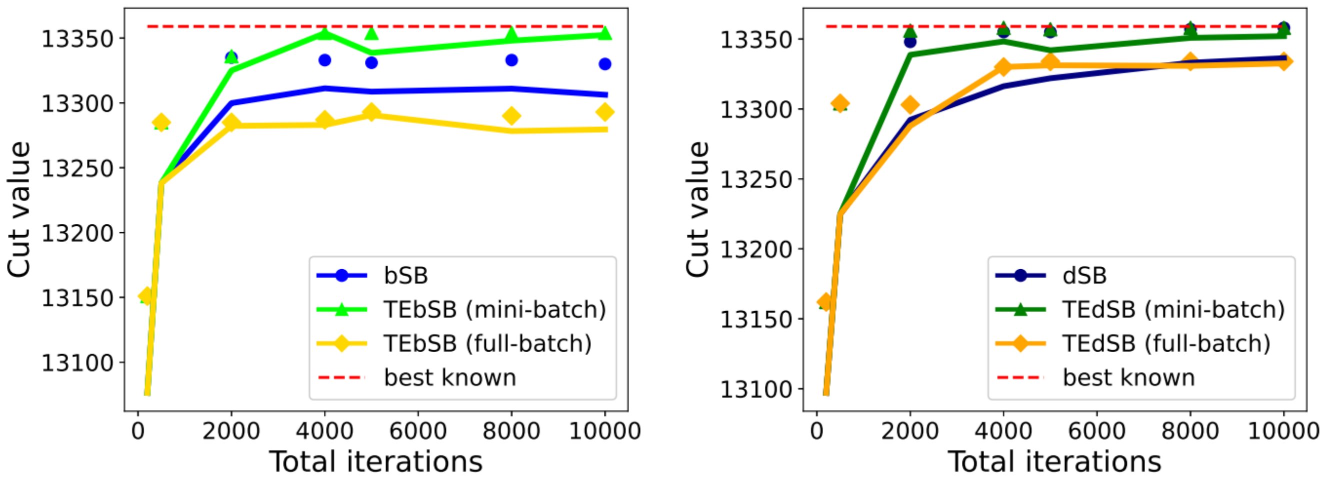


XZ Tao, QG Zeng, ZJ Huang, BW Zuo, J Zhuang, H Okawa, MH Yung, under review

Further Improvement in Quantum-Inspired

- Much improved values obtained for G-set Max-Cut benchmark dataset.
- **Visible improvement in both minimum energy prediction & computing time** for TrackML datasets.

Max-cut values from G22 instance



Minimum energy predictions from TrackML datasets

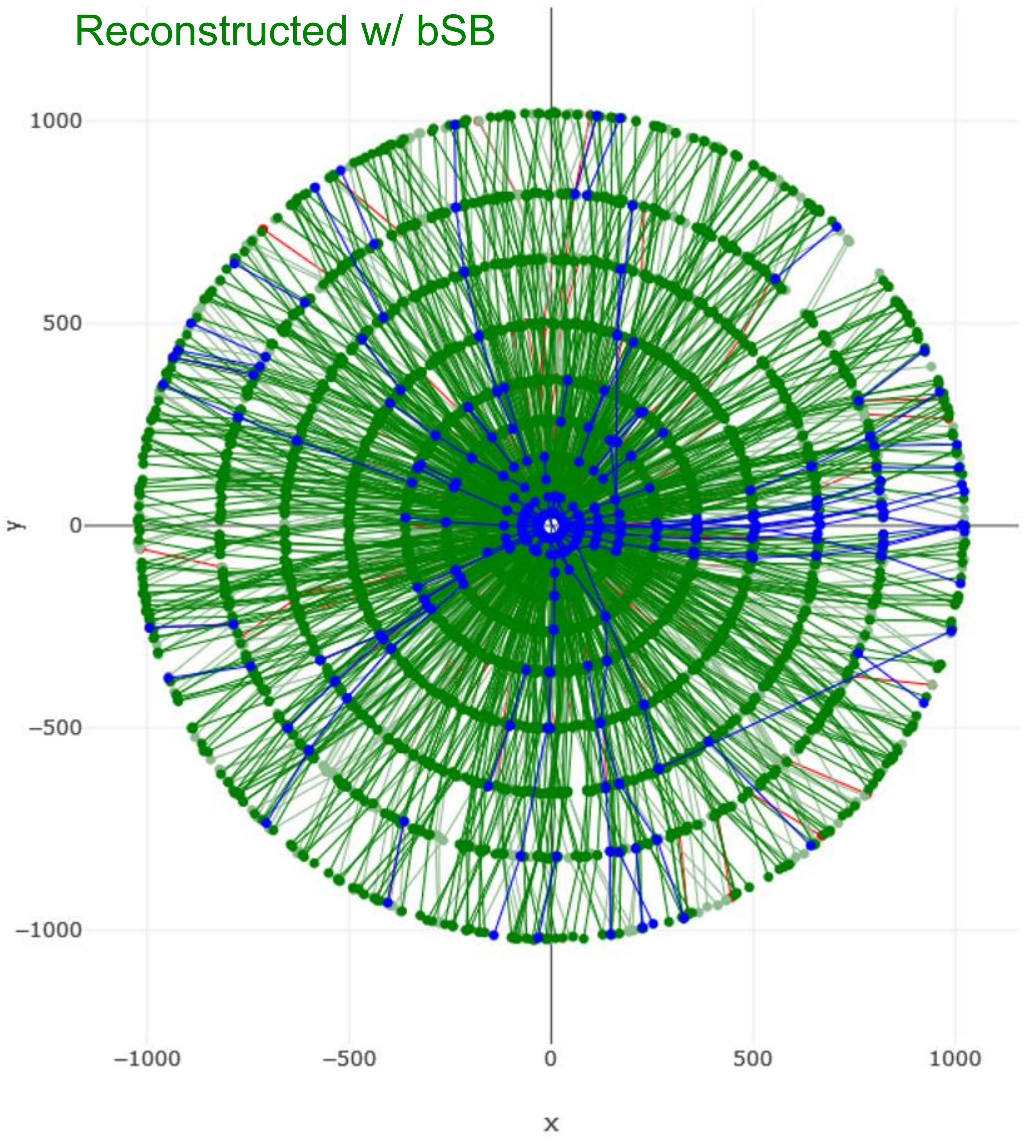
	bSB		TEbSB		dSB		TEdSB	
	Time (s)	Energy (a.u.)	Time (s)	Energy (a.u.)	Time (s)	Energy (a.u.)	Time (s)	Energy (a.u.)
ev1004 (N=109498)	8.67	-448998	7.25	**-449363**	9.02	-447488	7.43	-449349
ev1014 (N=78812)	5.06	-263353	4.27	**-263650**	5.24	-261860	4.33	-263641
ev1023 (N=80113)	5.33	-261244	4.42	-261345	5.48	-260928	4.80	**-261362**

Summary

References:

- H. Okawa, Spinger CCIS 2036 (2024) 272, arXiv:2310.10255
- H. Okawa, et al., Springer Comput. Softw. Big Sci. 8, 16 (2024)
- H. Okawa, et al., Phys. Lett. B 864 (2025) 139393
- XZ Tao et al., under review

- Quantum computing applications are an emerging field in high energy particle and nuclear physics.
- Various reconstruction tasks can be formulated as QUBO/Ising problems.
- **Quantum-inspired algorithms (bSB in particular) significantly outperforms QAOA & quantum annealing for QUBO tracking & jet clustering.**
- Tracking:
    - **We demonstrated a promising application of simulated bifurcation in HEP for the first time.**
    - **bSB can directly handle the HL-LHC datasets and provides four orders of magnitude speed-up with 1 GPU from D-Wave Neal** & can be considered for implementation **now**.
- Jet reconstruction:
    - **This is the first successful demonstration of global multijet reconstruction w/ QUBO formulation.**
      At present, only bSB can predict reasonable Ising energy for multijet reconstruction QUBOs.
    - **Moreover, bSB provides improved jet energy resolution for multijet events.**
- **We have also succeeded in improving the SB quantum-inspired algorithms further.**
  Applications to specific high-energy physics problems are under way.



Thank you for listening!