



Quantum AI for Pattern Recognition at High-Energy Colliders ~ Tales of Three “Quantum’s” ~

IAS Program on Fundamental Physics (FP 2026), January 12-16, 2026

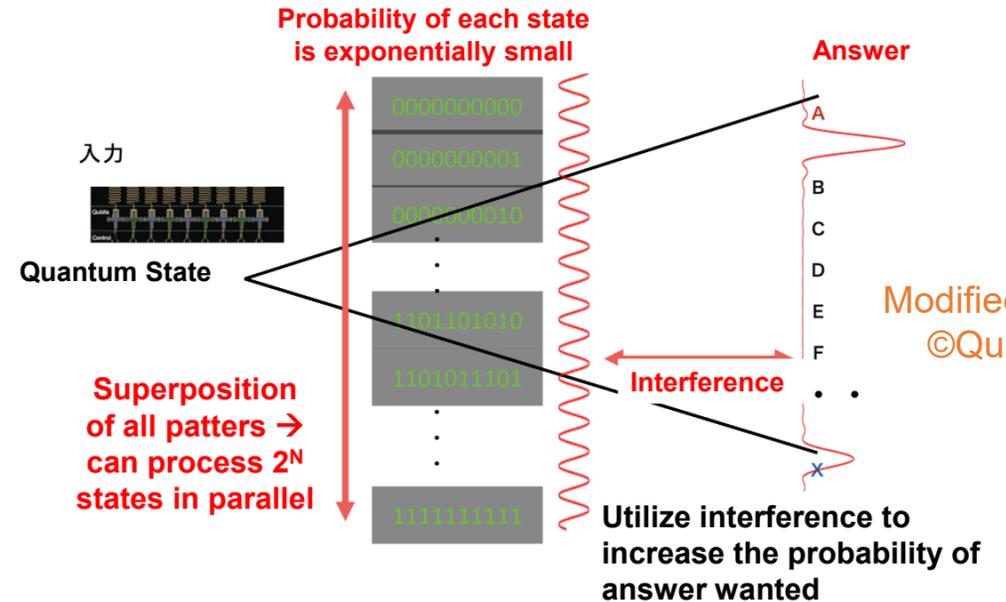
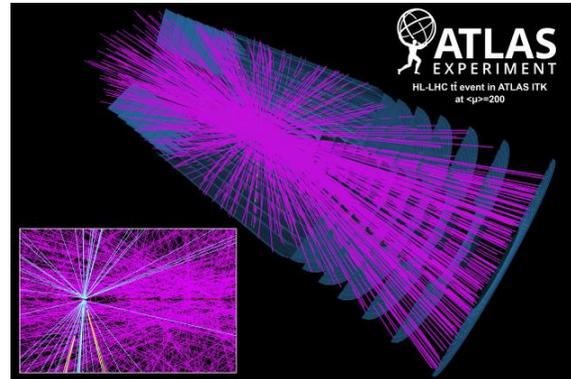
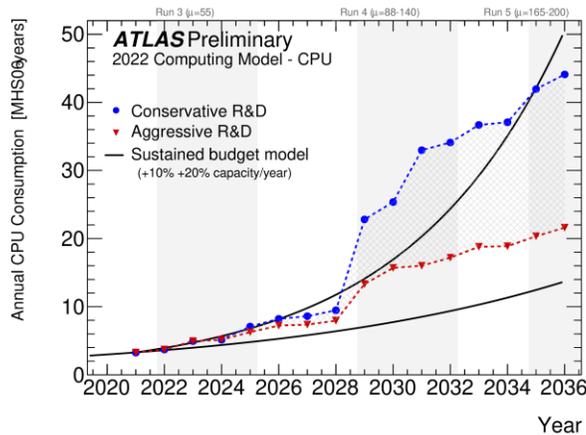
Hideki OKAWA (大川英希)

Institute of High Energy Physics, Chinese Academy of Sciences

A talk based on my recent review: [H. Okawa, arXiv:2511.16713](#)

Why Quantum Computing?

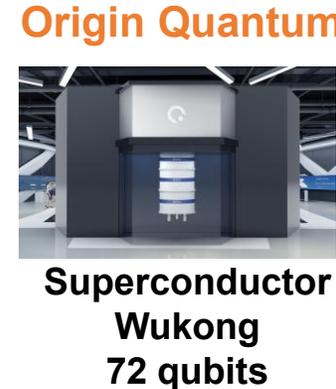
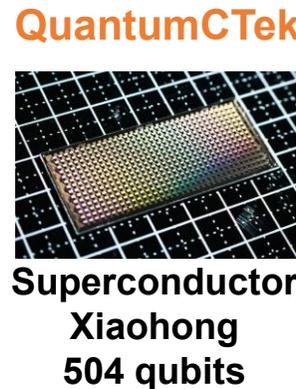
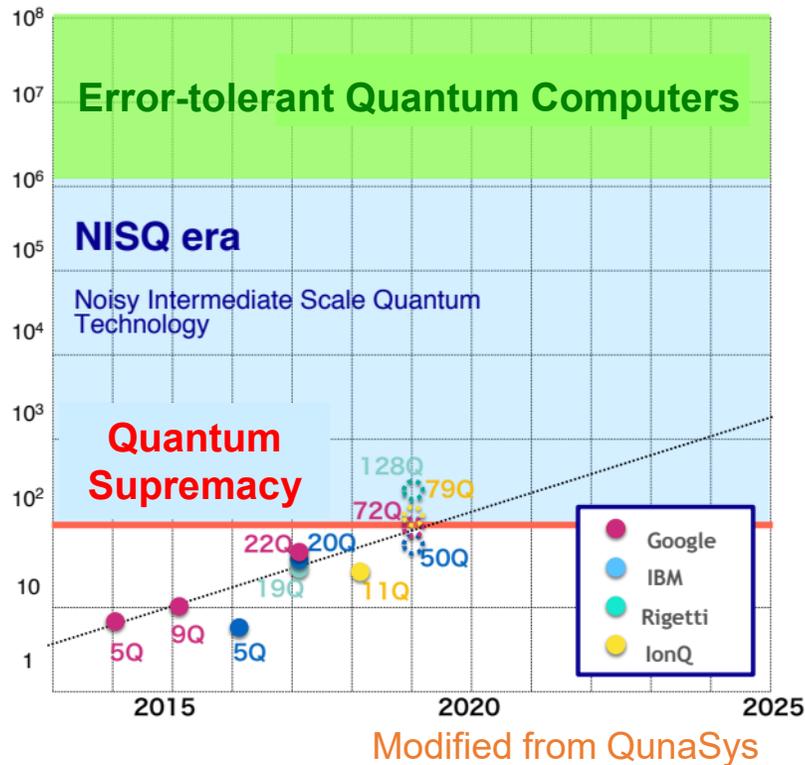
Experiments



- Future colliders (e.g. HL-LHC, CEPC, EIC) 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.**
- **Innovation in computing is eagerly awaited.**

- Through superposition, entanglement, interference (& tunneling for annealing), quantum computers may bring in exponential speed-up.
- **Quantum+AI may allow us to perform computation that was not possible before.**

Noisy Intermediate Scale Quantum



- Now is the era of Noisy Intermediate Scale Quantum (NISQ) computers (>~50 qubits).
- Current applications using quantum computing hardware all faces limitations from the number of available qubits & hardware noise.

3 Quantum Computing Technologies

H. Okawa (invited review), arXiv:2511.16713, submitted to MPLA

Quantum Circuits

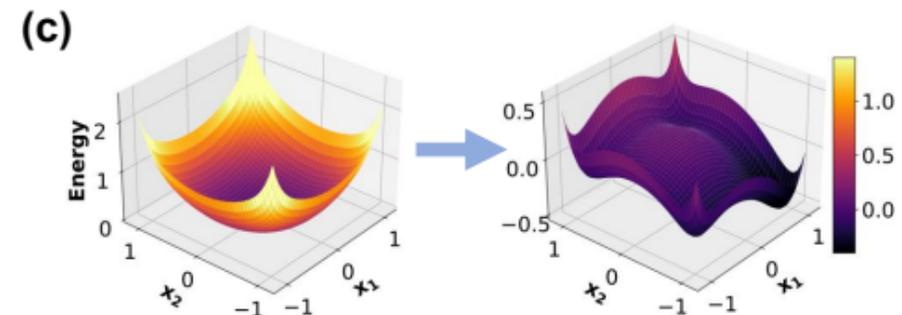
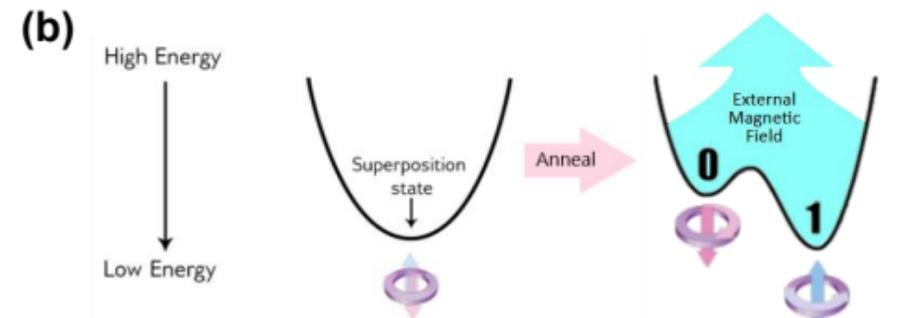
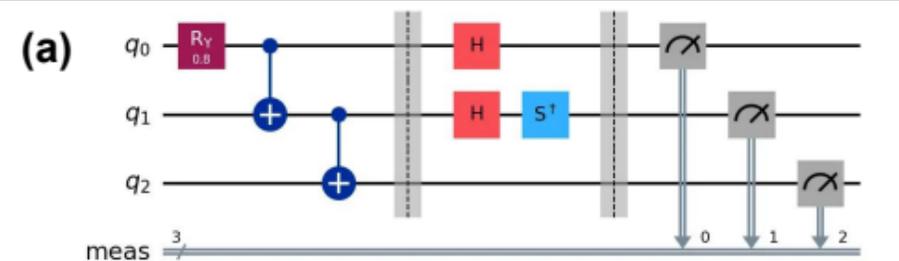
- Uses quantum logic gates. Is universal computing.
- **Most quantum computers adopt this approach.**

Quantum Annealing

- Uses the adiabatic theorem to seek Hamiltonian ground states.
- Is non-universal, **only applicable to optimization problems.**

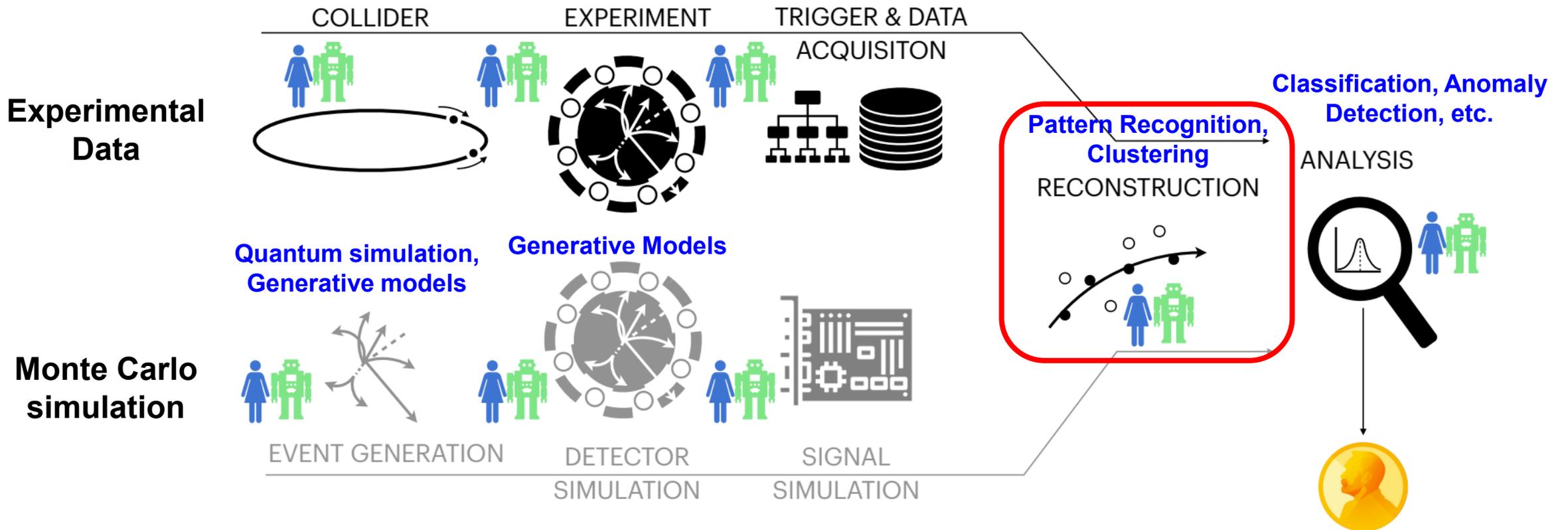
Quantum-inspired

- Classical algorithms inspired by quantum computing concepts: Simulated annealing, simulated bifurcation, tensor networks, etc.



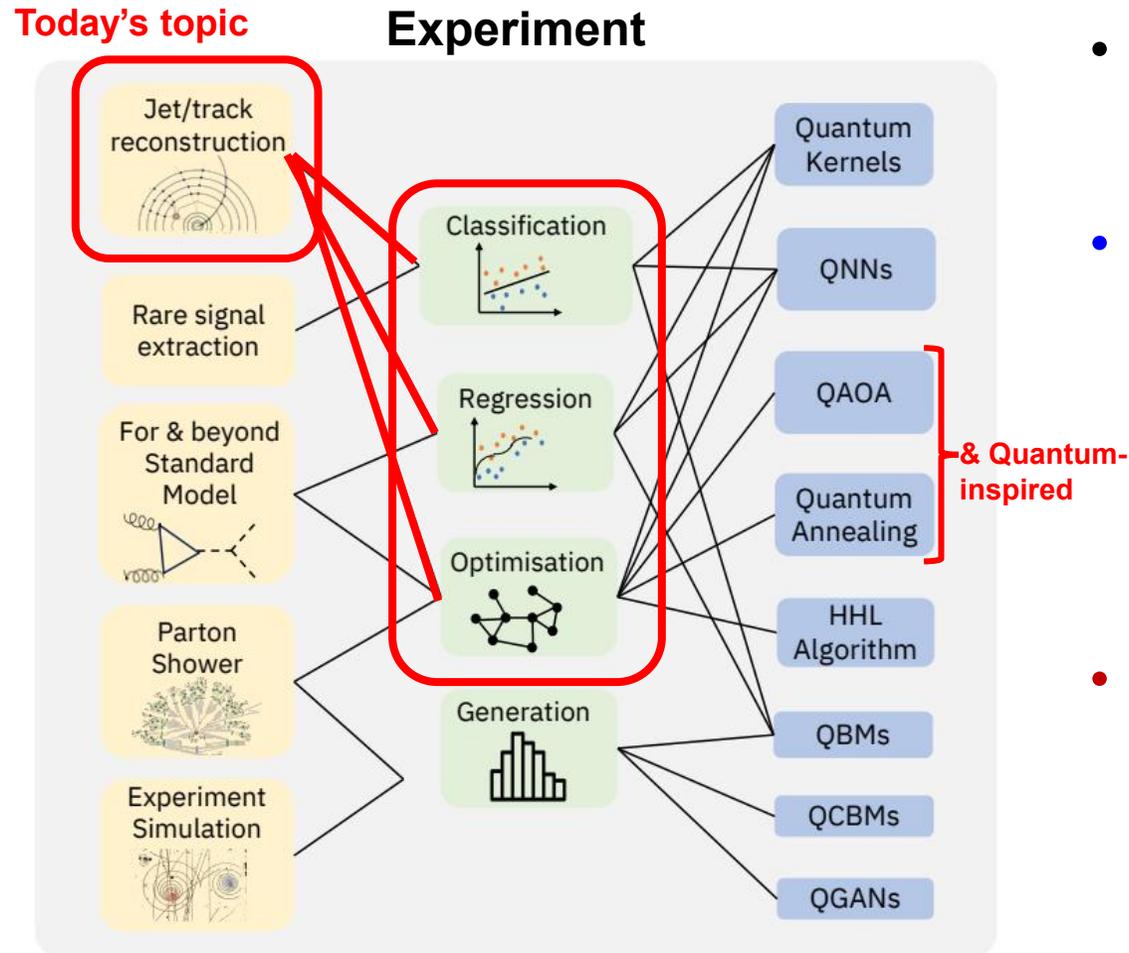
Experimental Workflow at Colliders

Credits: Andreas Salzburger



- **All steps require a significant amount of computing resources!**
- **State-of-the-art AI is currently being introduced/considered at all levels.**
- **Can we introduce quantum computing to these tasks?**

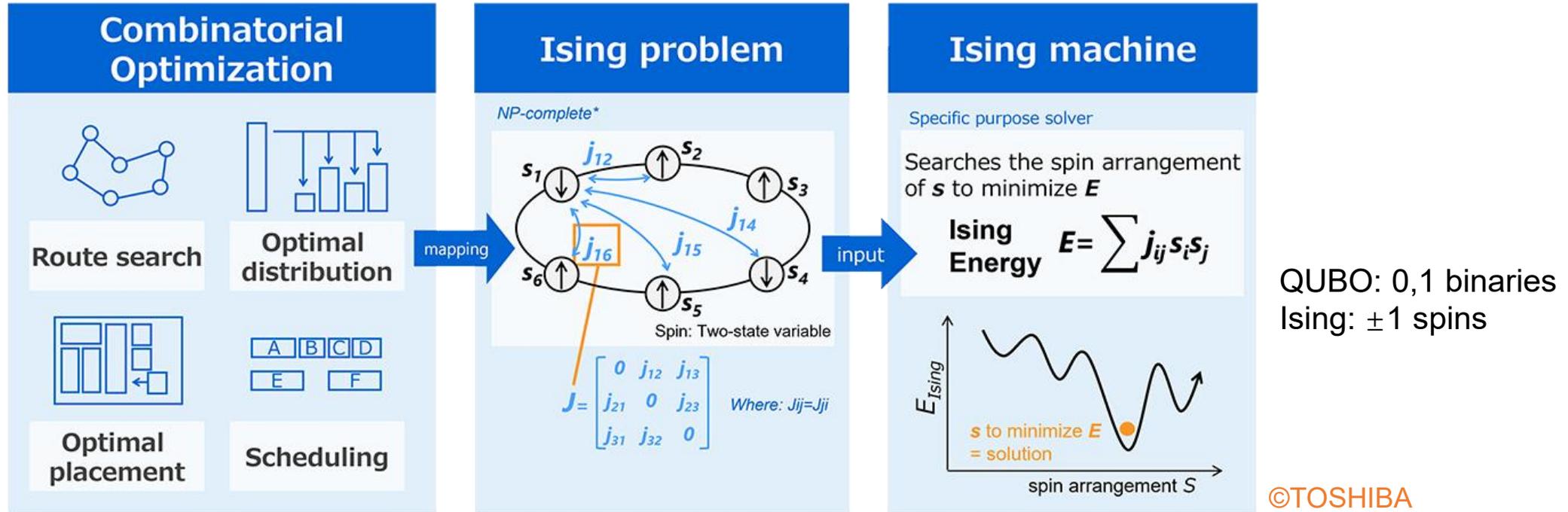
QC Applications in HEP Pattern Recognition



QC4HEP Whitepaper: A. Di Meglio et al., PRX
QUANTUM 5, 037001 (2024)

- Two classes of algorithms exist for both track and jet reconstruction.
- **Iterative: e.g. Combined Kalman filter (tracking), sequential jet clustering (k_t , anti- k_t , etc.)**
 - **Requires quantum associative memory (QuAM; not yet available).**
- **Global: e.g. Hough transform, XCone jet clustering**
 - **Global reconstruction can be formulated as combinatorial optimization (= Ising/QUBO) problems.**

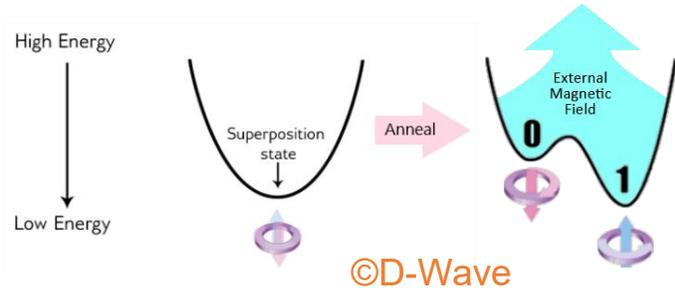
Ising/QUBO Problems



- Combinatorial optimization problems are non-deterministic polynomial time (NP) complete problem: no efficient algorithm exists to find the solution.
- They can be mapped to Ising/QUBO problems. **Ising/QUBO Hamiltonians are designed so that the ground state corresponds to the answer.**
- **Track & jet reconstruction can also be formulated as such problems.**

3 Classes of Ising Problem Solvers

Quantum Annealing (QA)

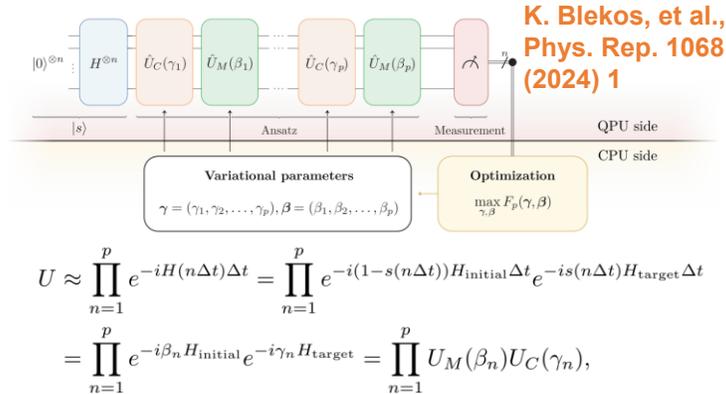


$$H(s) = A(s)H_{\text{initial}} + B(s)H_{\text{target}}$$

- Hamiltonian is slowly modified from a symmetric initial form to the target Hamiltonian describing the Ising problem.
- Quantum adiabatic theorem supports the success of obtaining the ground state.
- **Quantum tunneling** helps avoid local minima.

Hideki Okawa

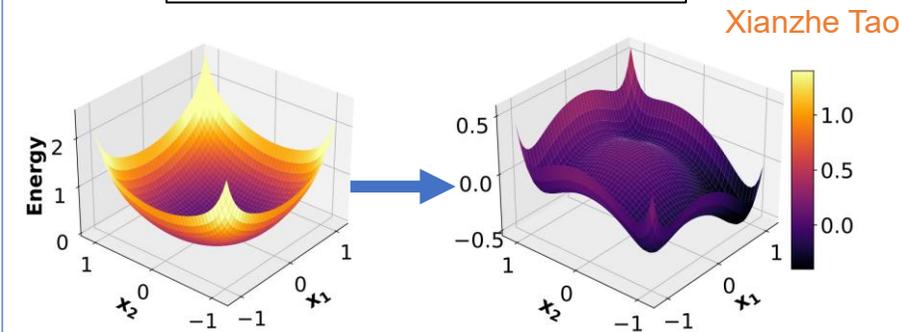
Quantum Circuits



- **Quantum Approximate Optimization Algorithm (QAOA)** mimics quantum annealing with Trotterization.
- Imaginary Hamiltonian variational ansatz (iHVA) & Imaginary Time Evolution-Mimicking Circuit (ITEMC) overcome some known bottlenecks of QAOA.

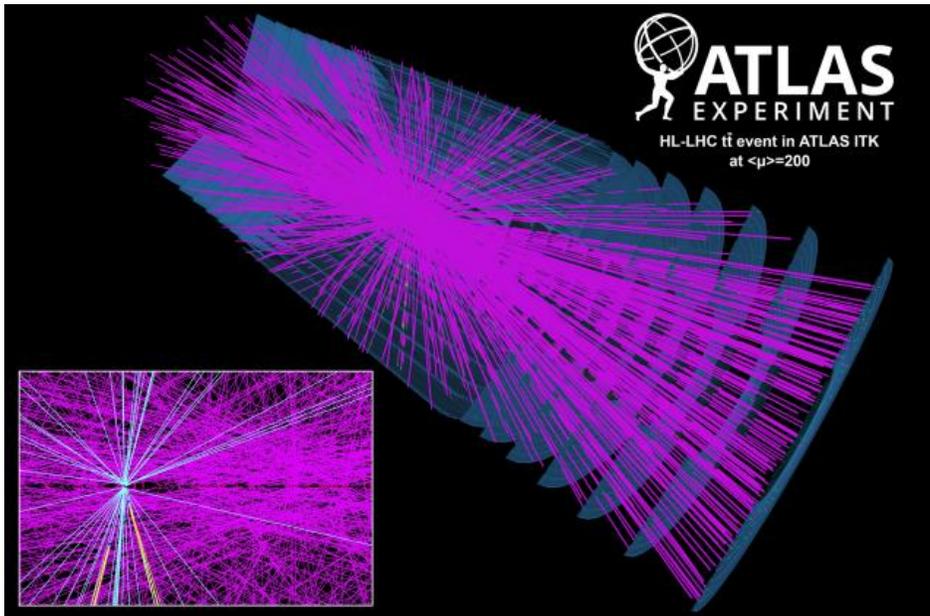
HKUST IAS FP 2026

Quantum-Inspired

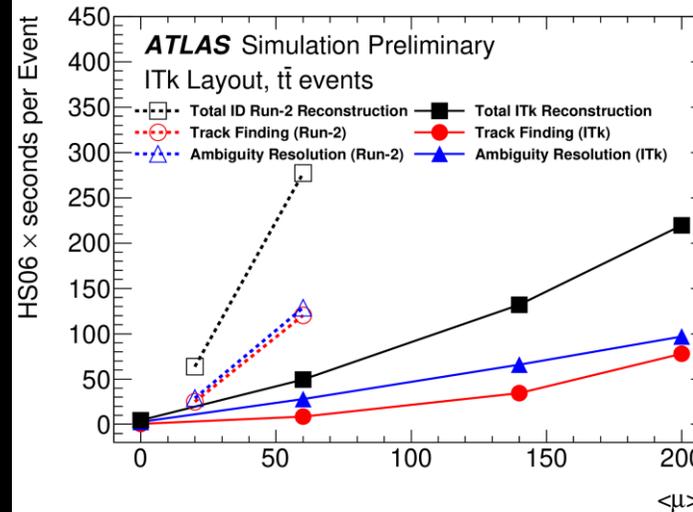


- Quantum-inspired runs on classical hardware with algorithms inspired by QC.
- **Simulated annealing (SA)** uses random moves in the solution space to search for the ground state.
- **Simulated bifurcation (SB) emulates quantum adiabatic evolution of Kerr-nonlinear parametric oscillators. It significantly outperforms SA.**
 - A new variant of such kind (tabu-enhanced SB) is recently developed (XZ Tao et al.). 8

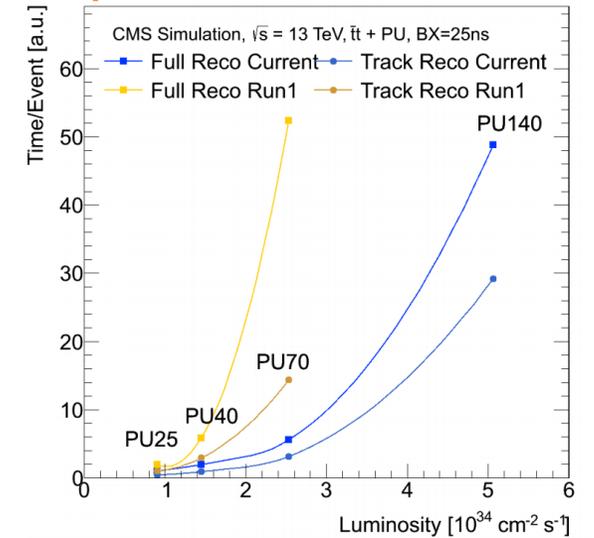
Track Reconstruction at LHC & HL-LHC



ATL-PHYS-PUB-2019-041



<https://cds.cern.ch/record/1966040>



- Tracking is an algorithm to reconstruct charged particle momenta from detector hits.
- **Computing time with traditional iterative methods increases exponentially against track multiplicity.**
- **ML-based approaches are actively investigated, but quantum algorithms may play an important role.**

	Run 1	Run 2	HL-LHC
μ	21	40	150-200
Tracks	~280	~600	~7-10k

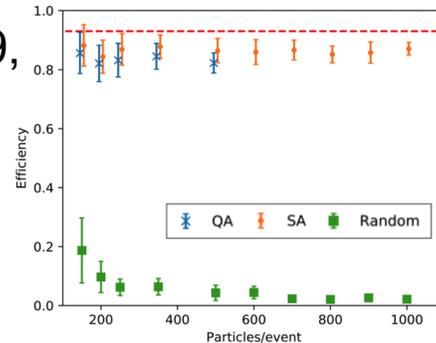
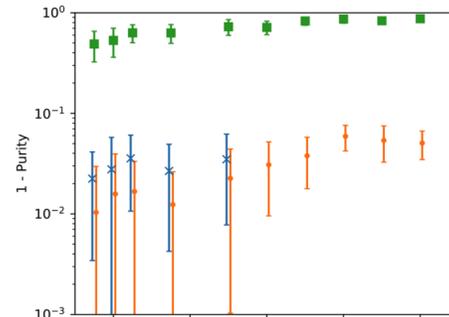
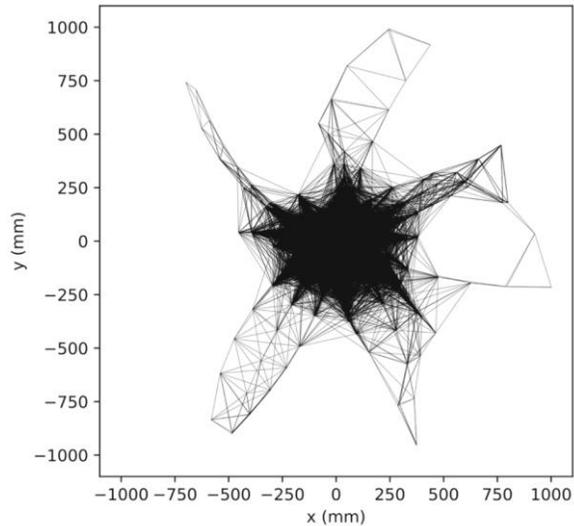
Global Track Reconstruction - Doublets

Doublet-based

A. Zlokapa et al., *Quantum Mach. Intell.* 3, 27 (2021)

Denby-Peterson Hamiltonian

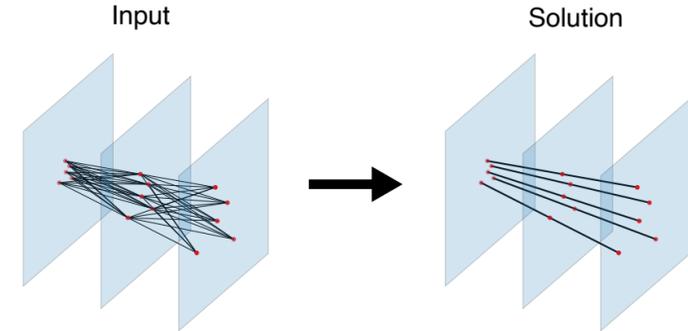
$$E = - \sum_{a,b,c} \left(\frac{\cos^\lambda(\theta_{abc}) + \rho \cos^\lambda(\phi_{abc})}{r_{ab} + r_{bc}} \right) s_{ab}s_{bc} + \eta \sum_{a,b,c} \left(z_c - \frac{z_c - z_a}{r_c - r_a} r_c \right)^\zeta s_{ab}s_{bc} + \alpha \left(\sum_{b \neq c} s_{ab}s_{ac} + \sum_{a \neq c} s_{ab}s_{cb} \right) - \sum_{a,b} (\beta P(s_{ab}) - \gamma) s_{ab},$$



- A Denby-Peterson algorithm (1988/1989, originally used in LEP) modified for HL-LHC was tested **up to 500 particles (hardware limitation)** for QA.
- Comparable performance b/w QA & SA.

D. Nicotra et al., *JINST* 18 P11028 (2023)

LHCb

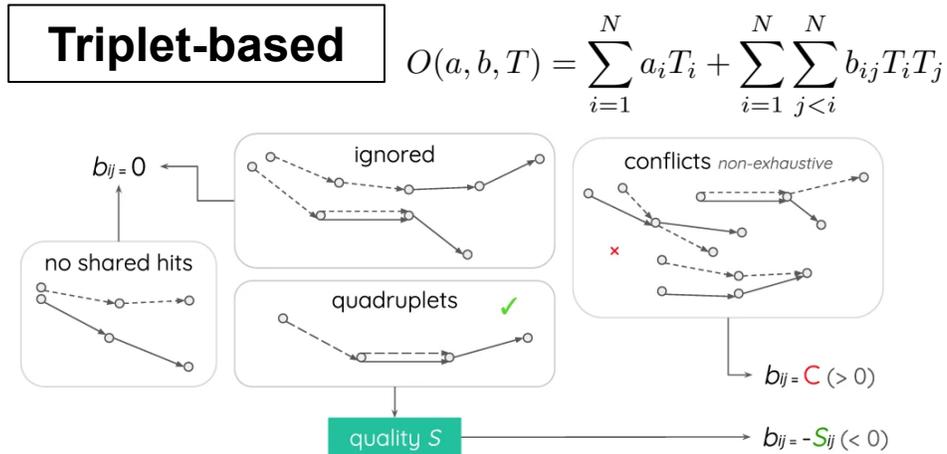


- A doublet-based Denby-Peterson Hamiltonian was also tested in LHCb with Harrow-Hassadim-Lloyd (HHL) algorithm.
- Simplified dataset **up to 5 particles** were adopted to run on IBM Hanoi quantum circuit hardware (27 qubits).

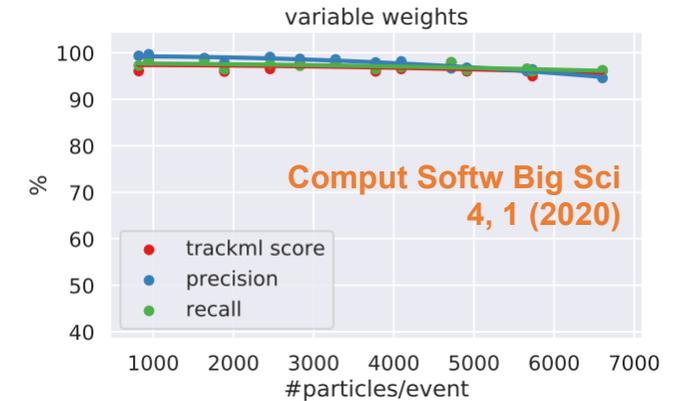
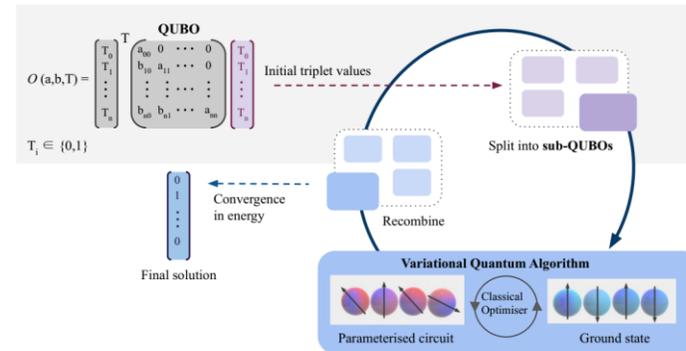
Layers	Particles	Doublets	Qubits	Depth	2-qubit gates
3	2	8	8	12 071	5 538
3	3	18	12	1 665 771	834 417
3	4	32	12	901 255	442 694
3	5	50	14	14 515 229	7 107 317
4	2	12	10	185 817	93 213
4	3	27	12	1 714 534	840 780
4	4	48	14	14 197 046	7 110 044

Global Track Reconstruction - Triplets

F. Bapst et al., *Comput Softw Big Sci* 4, 1 (2020)

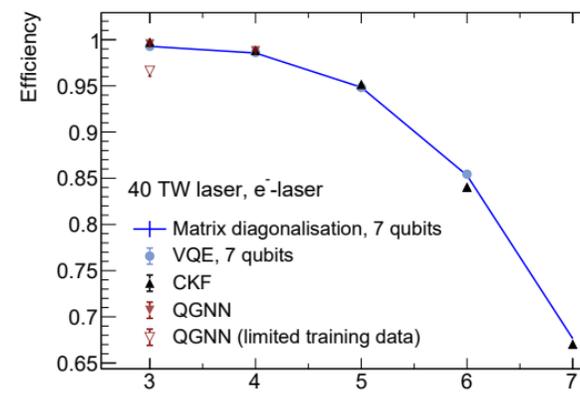


Sub-QUBO method

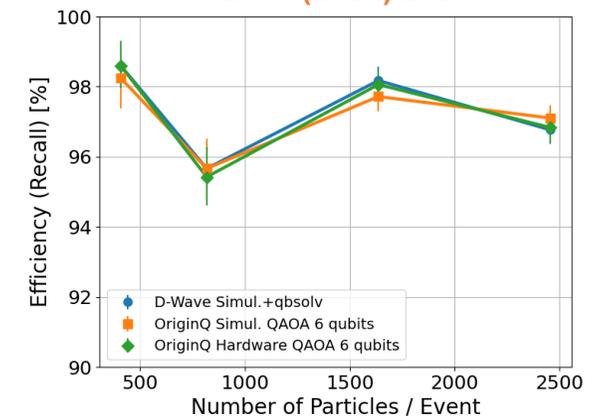


- Triplet-based approach simplifies the Hamiltonian & **reduces the number of qubits required.**
- Nevertheless, **HL-LHC conditions do not fit into current hardware** (needs $>O(10^5)$ qubits). Sub-QUBO methods have been used to split the problems. **→ This degrades computing speed by few orders of magnitude.**

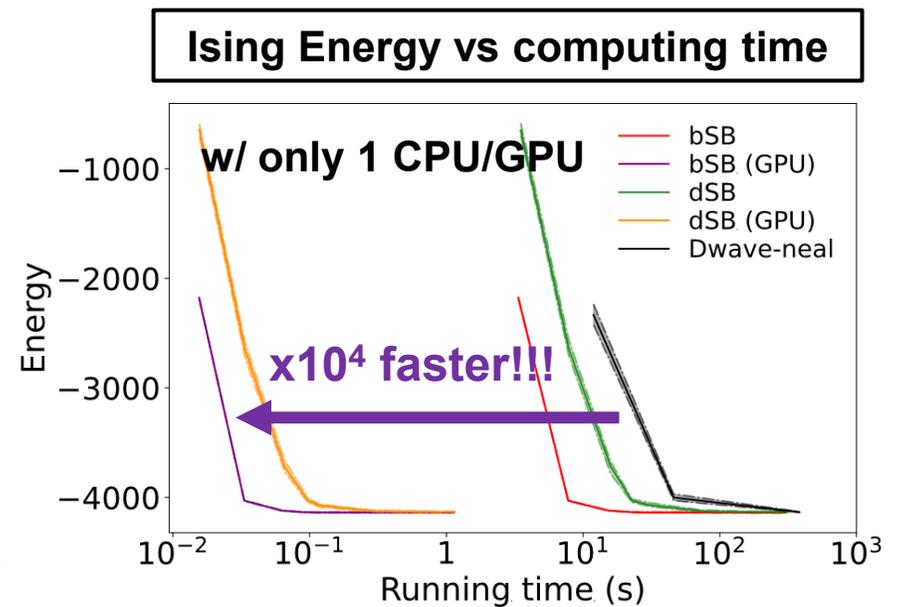
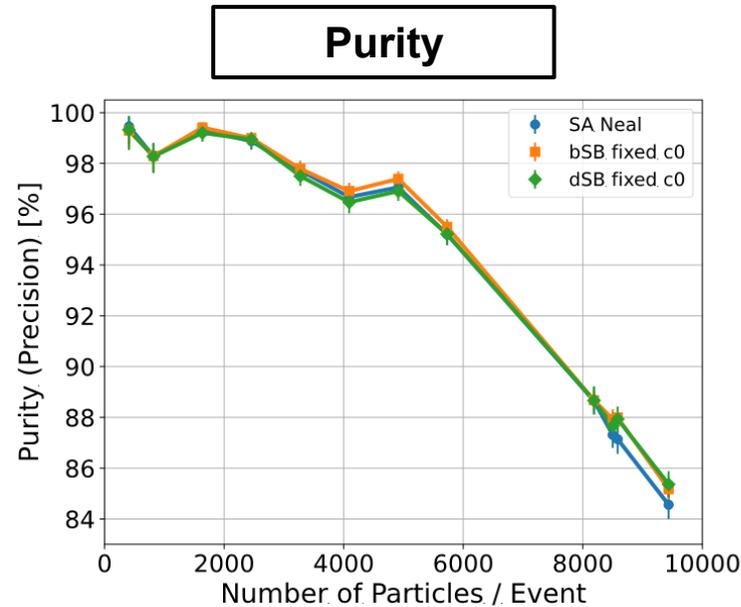
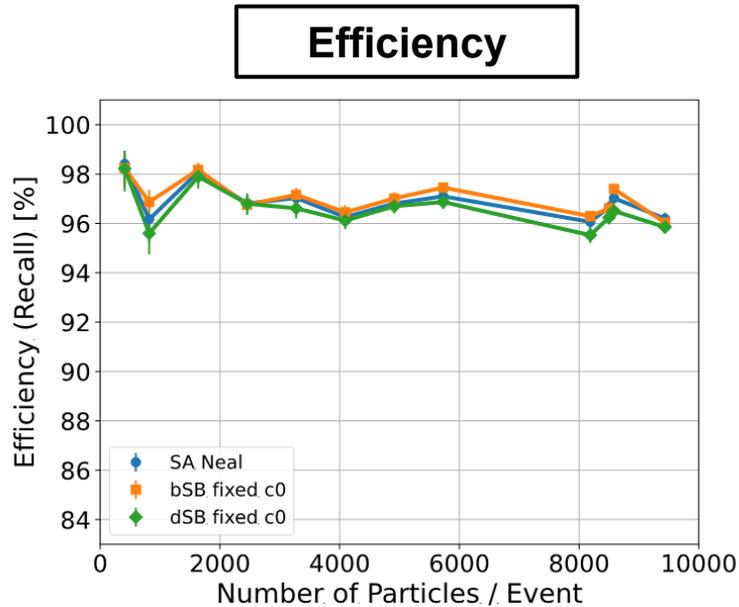
A. Crippa et al., *Comput Softw Big Sci* 7, 14 (2023)



H. Okawa, *Springer CCIS*, 2036 (2024) 272

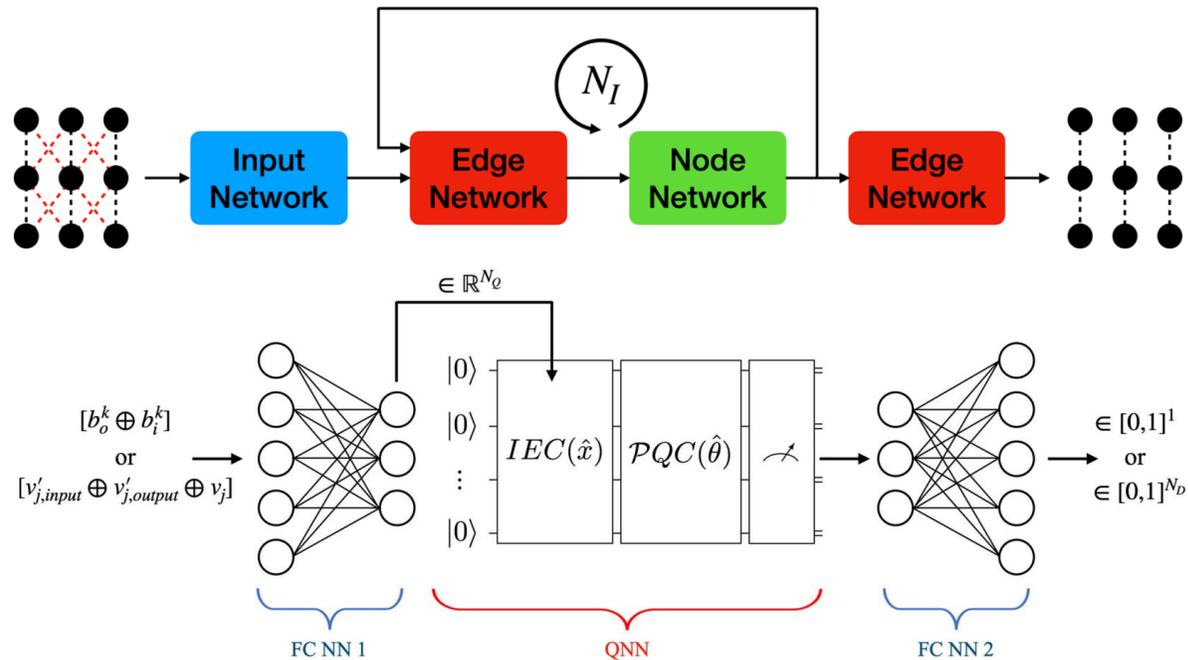


Global Track Reconstruction - Triplets

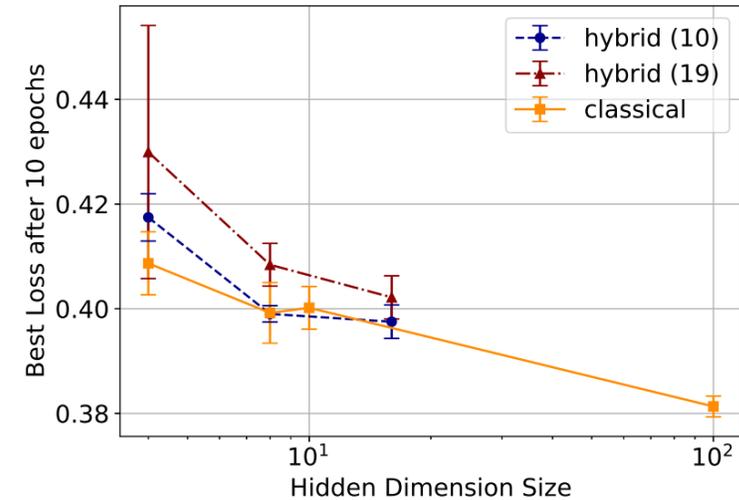


- **Quantum-annealing-inspired algorithm overcomes both the hardware limitation & computing speed bottleneck.**
- SB provides compatible or slightly better efficiency & purity than D-Wave Neal SA.
- A SB variant, bSB provides **4 orders of magnitude speed-up (23min → 0.14s) from D-Wave Neal SA** (cf. D-Wave hardware w/ sub-QUBO is ~2 orders of magnitude slower than Neal).
- **SB can effectively run w/ multiple processing, GPU & FPGA → Perfect match with HEP!!**

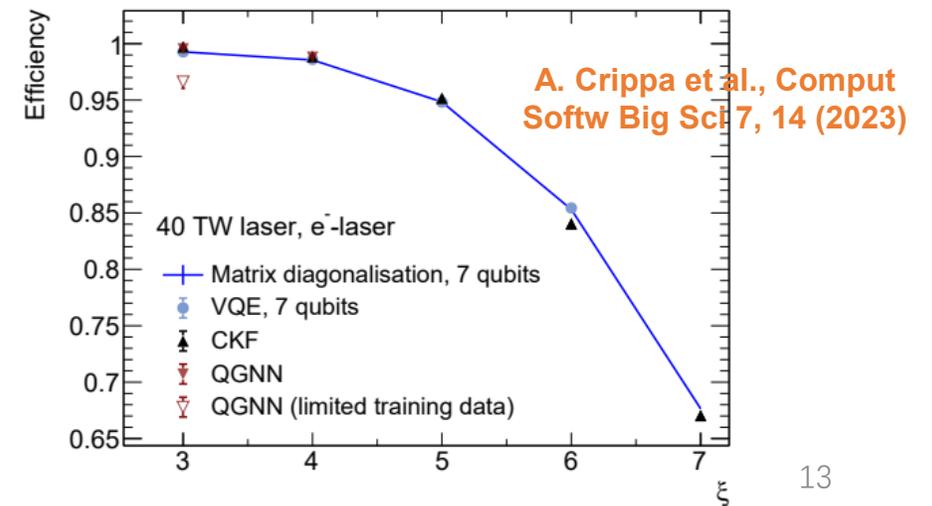
Global Track Reconstruction - QGNN



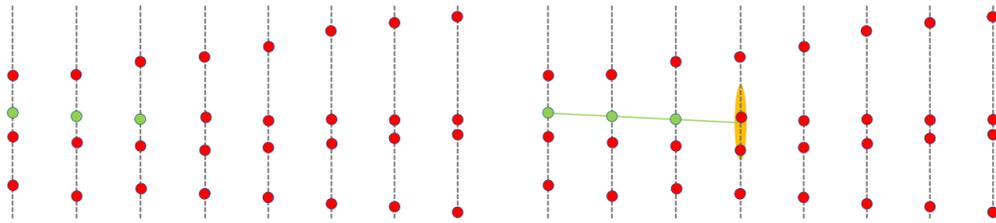
C. Tüysüz et al., *Quantum Mach. Intell.* 3, 29 (2021)



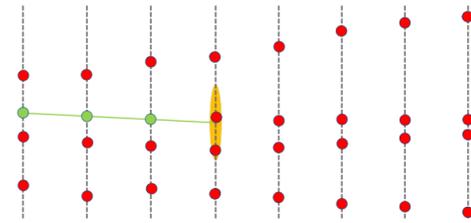
- Due to hardware limitation, only tested on quantum circuit simulator with 16 qubits (no noise).
- Requirements of very large RAM & long training time (>1 week) are currently the limiting factor.
- LUXE experiment also tested QGNN on low-intensity simulation data.



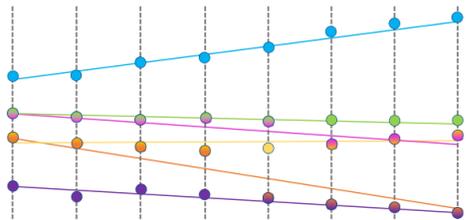
Track Reconstruction (Iterative)



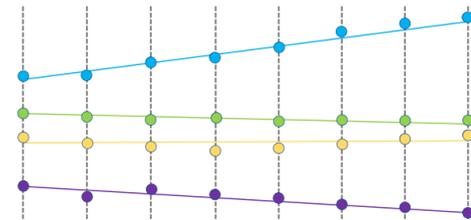
(a) Seeding



(b) Track building

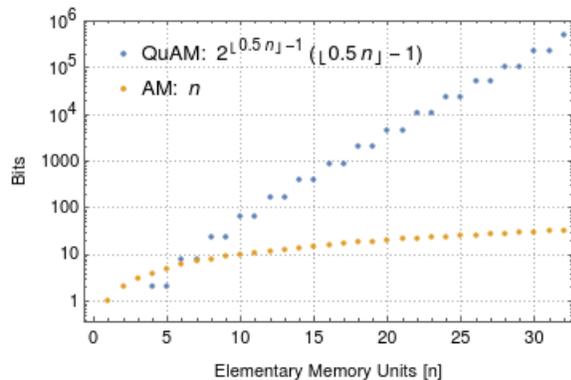


(c) Cleaning



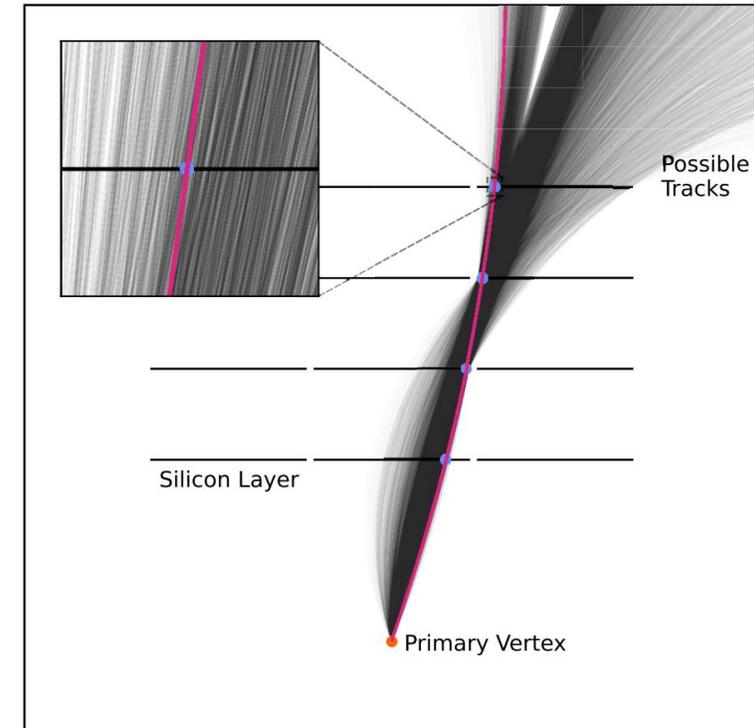
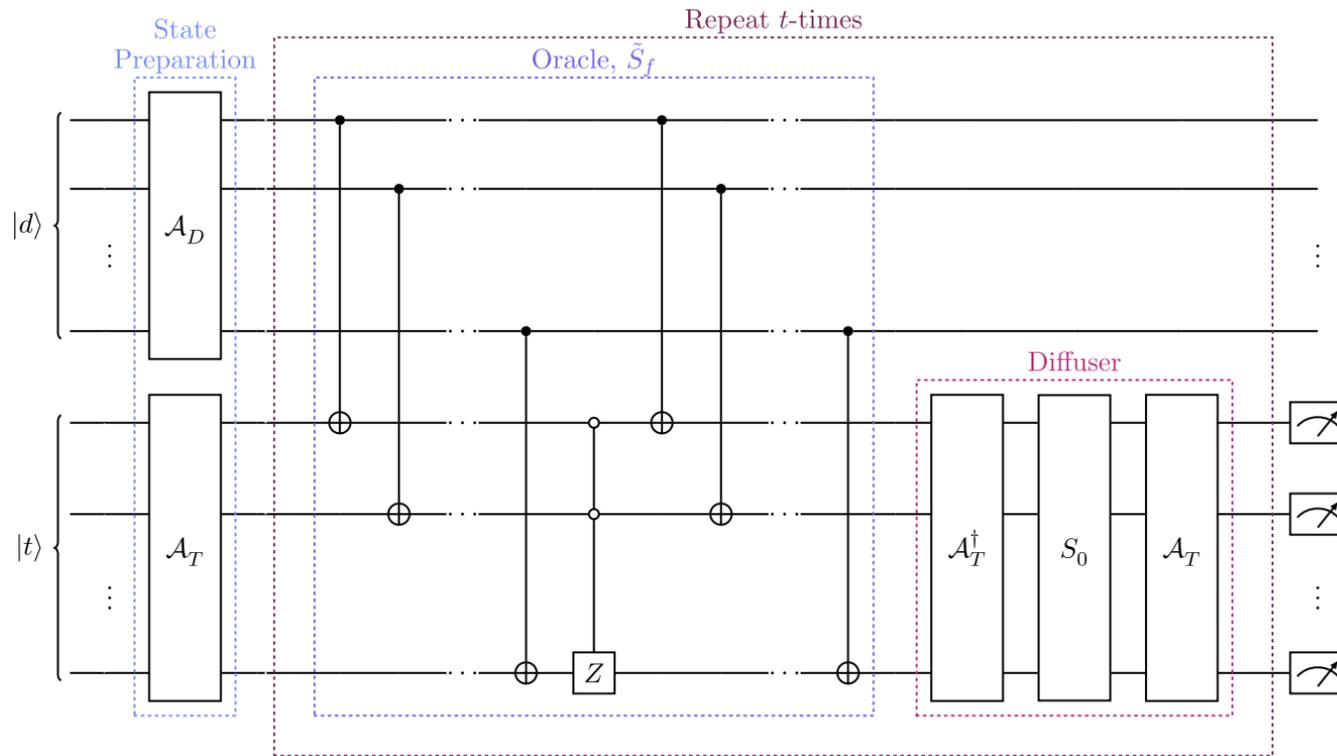
(d) Selection

- **Iterative reconstruction requires quantum associative memory (QuAM); not yet available**
- Conceptual complexity analyses were performed for the **four stages of track reconstruction**.
- **Grover search reduces complexity of seeding & track building in square root.**



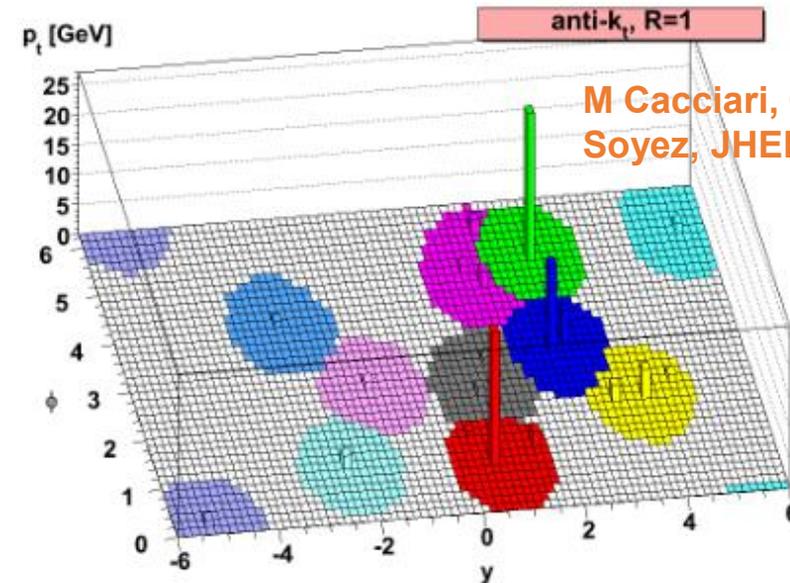
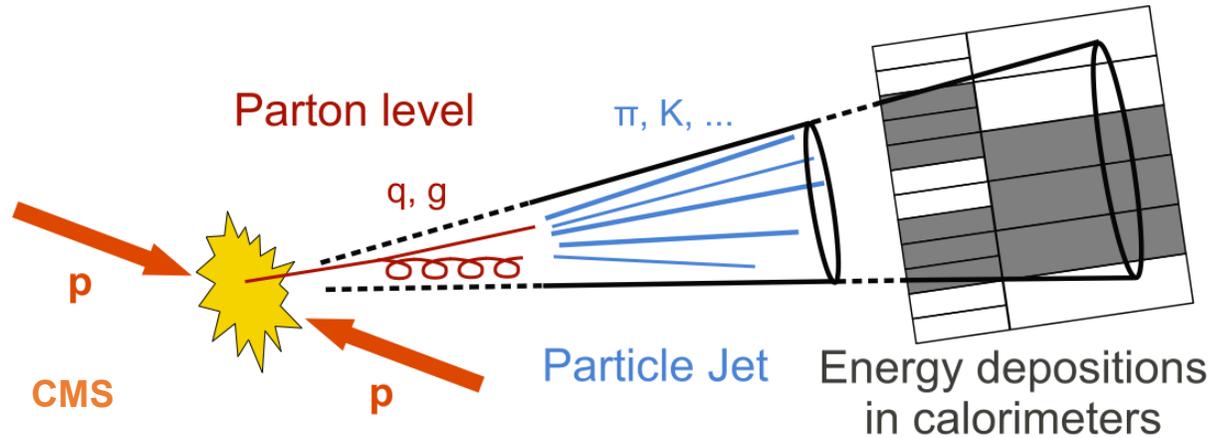
Tracking stages	Input size	Output size	Classical complexity	Quantum complexity
Seeding	$O(n)$	k_{seed}	$O(n^c)$	$\tilde{O}(\sqrt{k_{\text{seed}} \cdot n^c})$
Track Building	$k_{\text{seed}} + O(n)$	k_{cand}	$O(k_{\text{seed}} \cdot n)$	$\tilde{O}(k_{\text{seed}} \cdot \sqrt{n})$
Cleaning (original)	k_{cand}	$O(k_{\text{cand}})$	$O(k_{\text{cand}}^2)$	–
Cleaning (improved)	k_{cand}	$O(k_{\text{cand}})$	$\tilde{O}(k_{\text{cand}})$	–
Selection	$O(k_{\text{cand}})$	$O(k_{\text{cand}})$	$O(k_{\text{cand}})$	–
Full Reconstruction	n	$O(n^c)$	$O(n^{c+1})$	$\tilde{O}(n^{c+0.5})$
Full Reconstruction with $O(n)$ reconstructed tracks	n	$O(n)$	$O(n^{c+1})$	$\tilde{O}(n^{(c+3)/2})$

Track Reconstruction (Iterative)



- Iterative algorithm based on a novel oracle design, performed on a simplified detector with four layers of three tracking modules: **12 qubits to describe whether to consider the module hits.**
- Generalized Grover search (Quantum Amplitude Amplification) was demonstrated on a quantum circuit simulator.

Jet Reconstruction



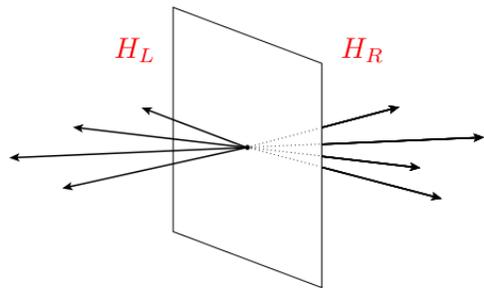
M Cacciari, GP Salam, G Soyez, JHEP 0804:063 (2008)

- Due to color confinement, gluons & quarks cannot exist on their own; they spray **collimated arrays of particles**.
- **Clustering those particles as jets provides important proxies to understand the original quark/gluon kinematics** but is a non-trivial & CPU-consuming task.
- **The standard jet clustering algorithms are (almost) all iterative** as global clustering is way too computing intensive.

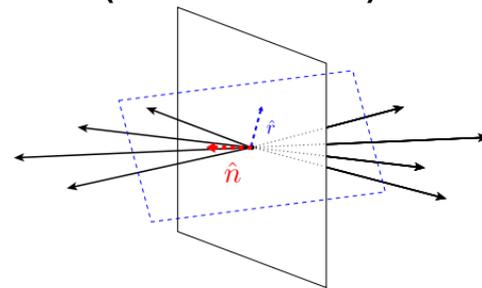
Jet Reconstruction (Iterative)

Iterative jet reconstruction also requires QuAM, so studies are mostly on complexity analyses.

Thrust as partitioning (QA)



Thrust as axis finding (Grover search)



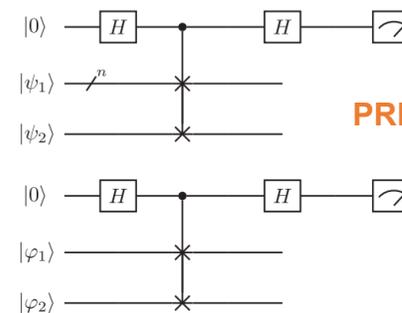
- Authors improved classical algorithm inspired by SISCone.
- **Quantum & classical algorithms scale the same, but for different reasons.**

Implementation	Time Usage	Qubit Usage
Classical ¹²⁴	$O(N^3)$	—
Classical with sort inspired by SISCONE ¹²⁵	$O(N^2 \log N)$	—
Classical with parallel sort	$O(N \log N)$	—
Quantum annealing	Gap dependent	$O(N)$
Quantum search: sequential model	$O(N^2)$	$O(\log N)$
Quantum search: parallel model	$O(N \log N)$	$O(N \log N)$

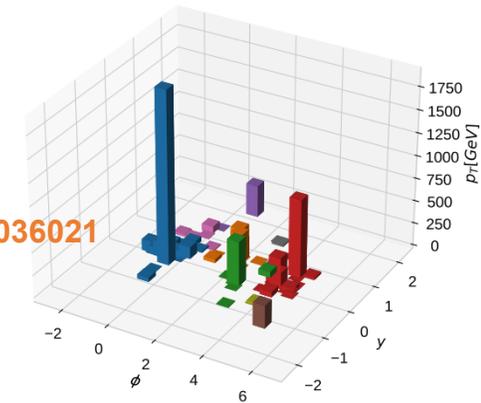
A. Wei, P. Naik, A.W. Harrow, J. Thaler, PRD 101, 094015 (2020),

Hideki Okawa

Quantum subroutine to compute Minkowski-based distance



PRD 106 036021



(b) Quantum anti- k_T , $p = -1$, $R = 1$, $\epsilon_c = 0.99$.

- **Quantum & classical algorithms [FastJet] scales the same for sequential clustering.**
- IBM quantum circuit simulator was also used to actually perform clustering.

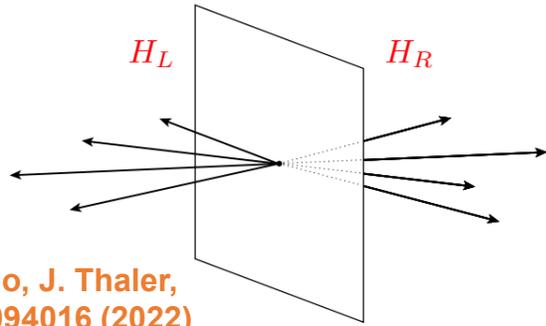
Jet algorithms	Classical	Quantum
K-means	$O(NKD)$	$O(NK \log D)$, ¹¹⁶ $O(N \log K \log(D-1))$ ¹²⁷
AP	$O(N^2TD)$	$O(N^2T \log(D-1))$ ¹²⁷
k_t , C/A, anti- k_t	$O(N^3)$ [suboptimal]	$O(N^2 \log N)$ ¹²⁷
	$O(N \log N)$ [FastJet] ^{132, 133}	$O(N \log N)$ ¹²⁷

¹¹⁶D. Pires, P. Bargassa, J. Seixas, Y. Omar, arXiv:2101.05618 (2021)

¹²⁷J.J. Martinez de Lejarza, L. Cieri, G. Rodrigo, PRD 106 036021 (2022)

Dijet Reconstruction (Global)

Quantum Annealing (Thrust)



A. Delgado, J. Thaler,
PRD 106, 094016 (2022)

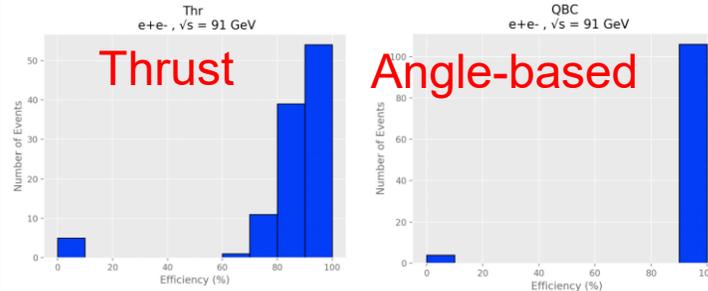
$$O_{\text{QUBO}}(\{x_i\}) = \left(\sum_{i=1}^N |\vec{p}_i| \right)^2 T(\{x_i\})^2$$

$$T(\{x_i\}) = 2 \frac{\left| \sum_{i=1}^N x_i \vec{p}_i \right|}{\sum_{i=1}^N |\vec{p}_i|}$$

- Quantum annealing with tuned annealing parameters & hybrid quantum/classical approach without tuned parameters exhibit similar performance to exact classical approaches.

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

Quantum Annealing (Angle)



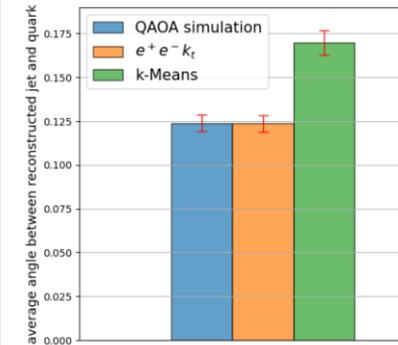
$$H = \frac{1}{2} \sum_{i,j=1}^N -\cos[\theta(\vec{p}_i, \vec{p}_j)] s_i s_j$$

- Angle-based approach shows more compatible clustering as ee- k_t for dijet events.
- However, **the same approach did not work for multijet events.** → Usage of multiple qubits for one hot encoding is prone to errors.

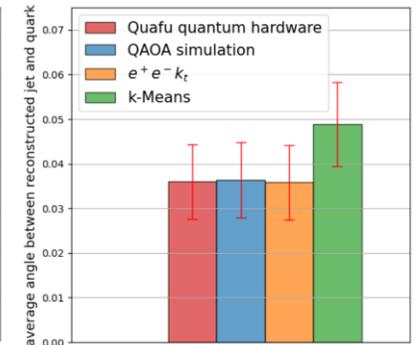
Y. Zhu et al., Sci. Bul. 70 (2025) 460

QAOA (Angle) or K-means

30-particle data
($e^+e^- \rightarrow ZH \rightarrow \nu\nu ss$)



6-particle data
($e^+e^- \rightarrow ZH \rightarrow \nu\nu ss$)



$$\hat{H}_C = \frac{1}{2} \sum_{(i,j) \in E} W_{ij} (I - \sigma_i^z \sigma_j^z)$$

W_{ij} : angle b/w particles i & j

- Used simplified/small-sized (6- or 30-particle) dijet events.
- Evaluated average angle w/ QAOA or K-means with Quafu hardware/simulator.

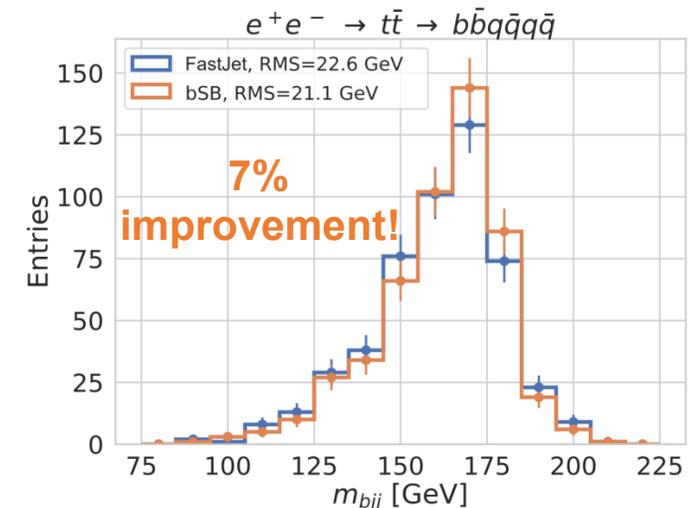
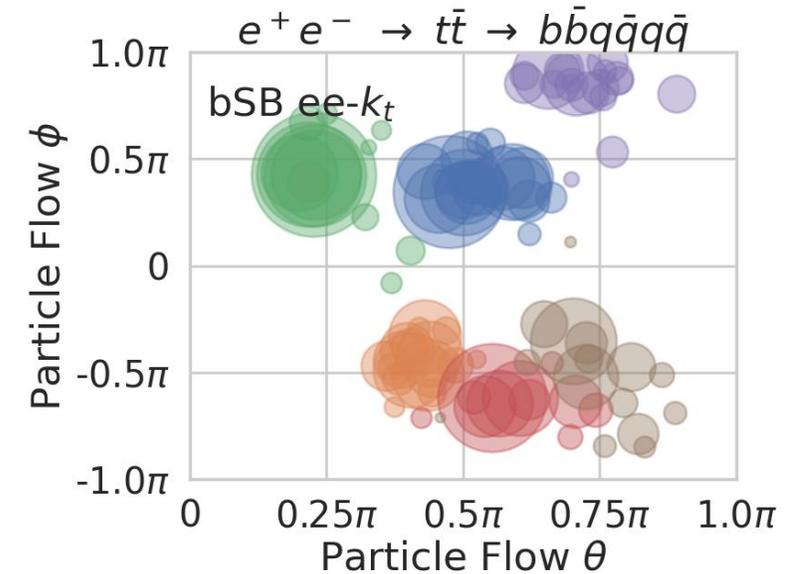
Multijet Reconstruction (Global)

QUBO Formulation

$$O_{\text{QUBO}}^{\text{multijet}}(x_i) = \underbrace{\sum_{n=1}^{n_{\text{jet}}} \sum_{i,j=1}^{N_{\text{input}}} Q_{ij} x_i^{(n)} x_j^{(n)}}_{\text{Defines distances b/w particle flow candidates}} + \lambda \underbrace{\sum_{i=1}^{N_{\text{input}}} \left(1 - \sum_{n=1}^{n_{\text{jet}}} x_i^{(n)}\right)^2}_{\text{Avoids double/none-assignment of particle flow candidates}},$$

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

- Quantum-inspired does not suffer from qubit-scaling & connectivity issues.
- **bSB quantum-inspired algorithm overcame the challenge from the one-hot encoding for multijet reconstruction.**
- **1st successful global multijet clustering w/ bSB quantum-inspired algorithm. → Opened up a practical path toward global jet reconstruction**
- **Invariant mass resolution improves by 6~7% for Higgs bosons/top-quarks.**



Prospects

- Quantum circuits in principle accelerate some components of reconstruction but **require QuAM architecture, error correction & increased # of qubits.**
- For quantum annealing, **increasing the connectivity** will be mandatory.
- It is also to be seen what quantum-centric supercomputing can bring to HEP.
- In any case, **some experimental tasks require $O(10^6)$ qubits. Quantum-inspired techniques will likely stay valuable.**

USTC Zuchongzhi-3

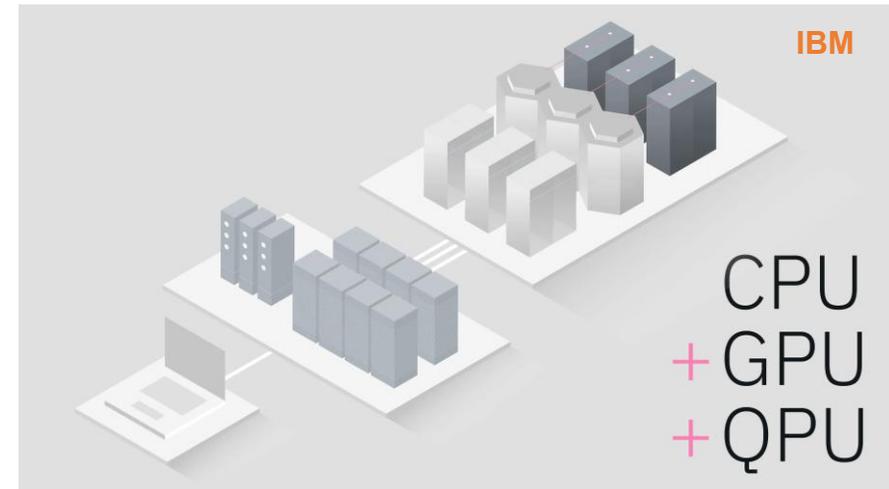


D. Gao et al., PRL 134 (2025) 090601

D-Wave Advantage2



Quantum-centric supercomputing



Summary

- Quantum AI application is an emerging field in high-energy physics.
- Three quantum technologies exist: (1) universal quantum gate machines, (2) quantum annealing & (3) quantum-inspired algorithms.
- Iterative reconstruction requires QuAM & studies are mostly at the conceptual level analyzing complexity.
- Global reconstruction studies are performed with all three technologies. Quantum hardware cannot cover the complete dataset, whereas quantum-inspired techniques are already feasible with promising computing speed.
- The rich program of HEP applications is likely to progress with constructive competitions among the three quantum technologies and other emerging techniques.
- For more details, please see my review: [H. Okawa, arXiv:2511.16713](#)

The background features a complex network of glowing blue and white lines and dots. The lines are thin and curved, creating a sense of motion and connectivity. The dots are small and bright, scattered throughout the scene. The overall color palette is cool, dominated by blues and whites, with a slight gradient from top to bottom.

Thank you for listening!

Tracking as Optimization Problem

- Tracks are formed by connecting silicon detector hits: e.g. triplets (segments w/ 3 hits).
- Doublets/triplets are connected to reconstruct tracks & it can be regarded as a **quadratic unconstrained binary optimization (QUBO)/Ising** problem.

$$O(a, b, T) = \underbrace{\sum_{i=1}^N a_i T_i}_{\text{Quality of triplets}} + \underbrace{\sum_i \sum_{j<i}^N b_{ij} T_i T_j}_{\text{Compatibility b/w triplet pairs}}$$

Quality of triplets

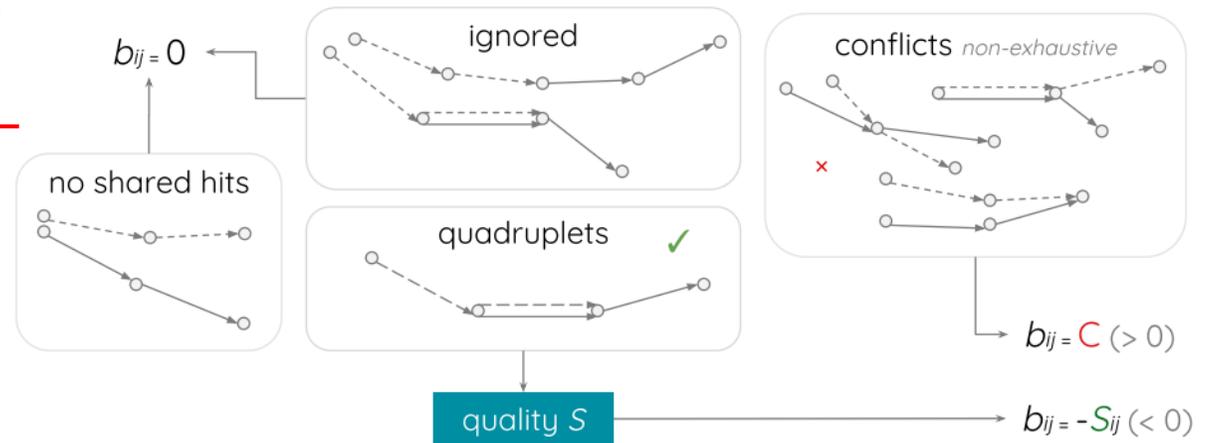
Compatibility b/w triplet pairs

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

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

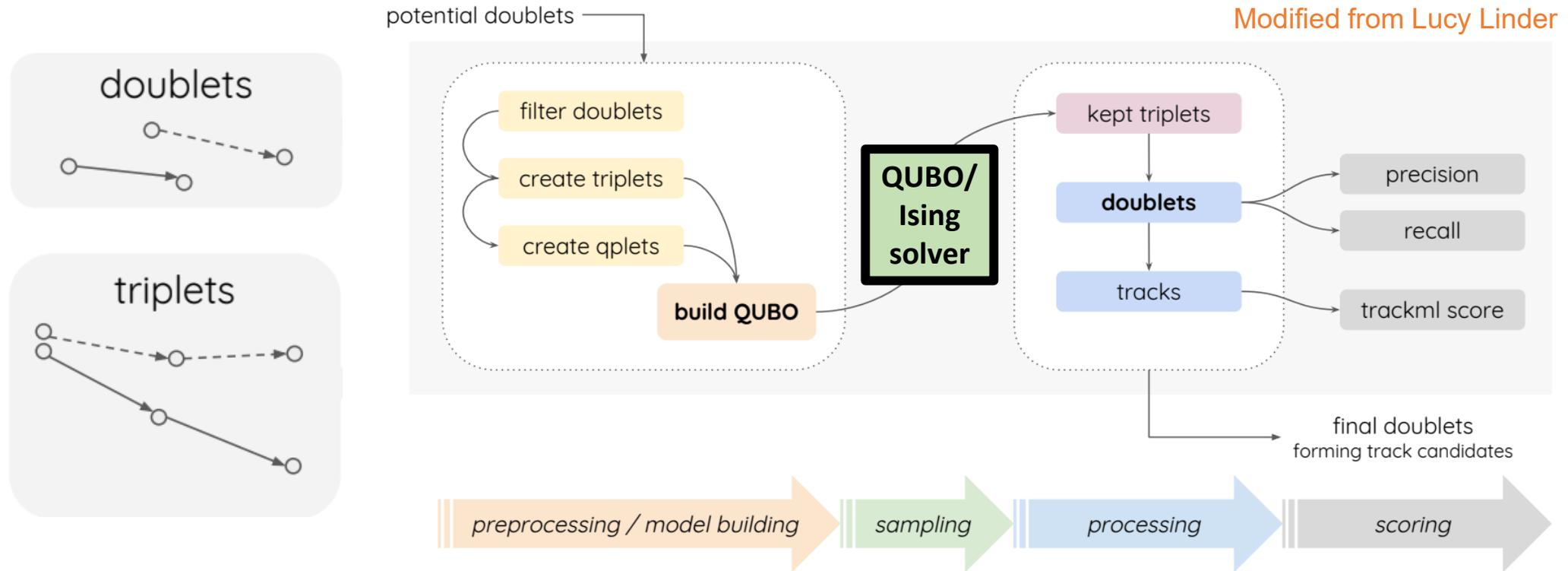
$$S_{ij} = \frac{1 - \frac{1}{2}(|\delta(q/p_{Ti}, q/p_{Tj})| + \max(\delta\theta_i, \delta\theta_j))}{(1 + H_i + H_j)^2},$$

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



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

Tracking Algorithm Flow w/ QUBO

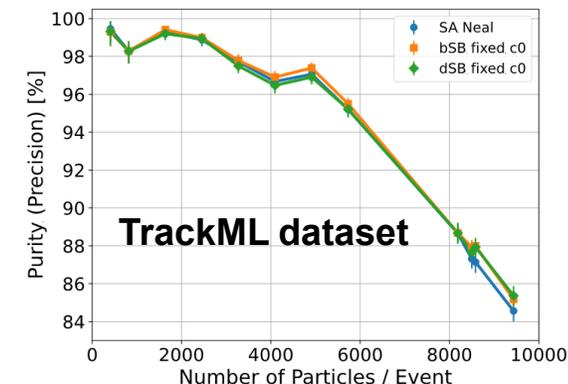
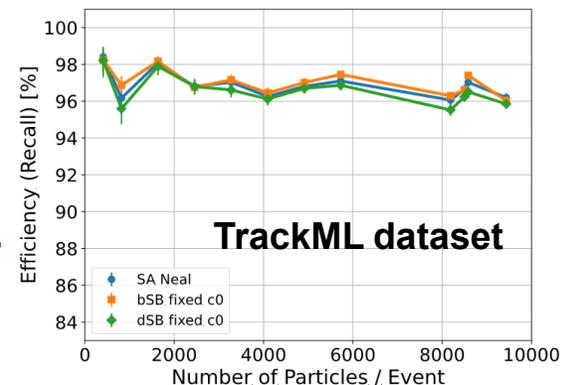


- We build QUBO on an event-by-event basis from the silicon detector hits.
- Predicted ground state will define which triplets should be kept (binary=1). Connecting the adopted triplets will give us the tracks.

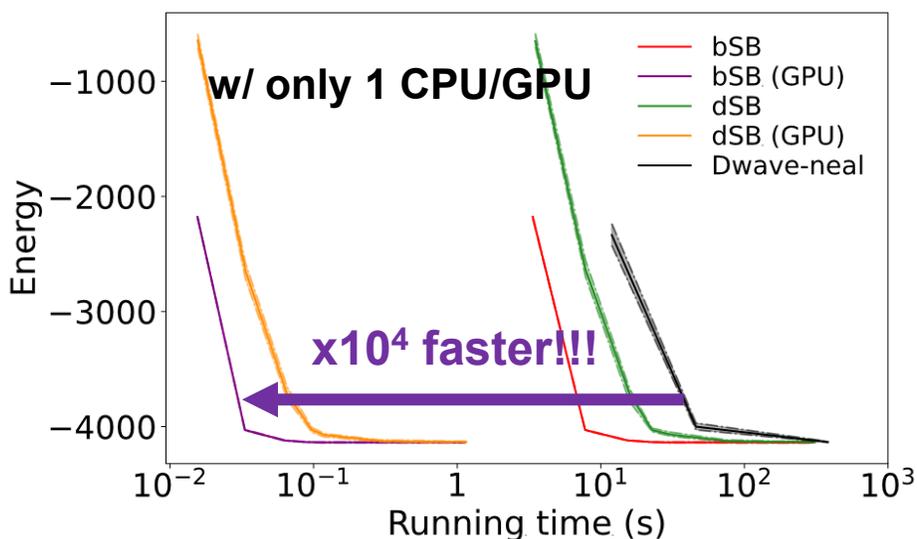
Tracking with Quantum-Inspired

- For some problems, quantum-inspired algorithms outperform quantum annealing.
- Ballistic simulated bifurcation (bSB) provides **4 orders of magnitude speed-up from D-Wave Neal simulated annealing** for HL-LHC data.
- SB can effectively run w/ multiple processing, GPU & FPGA.

No limitation on the problem size (up to ~million)



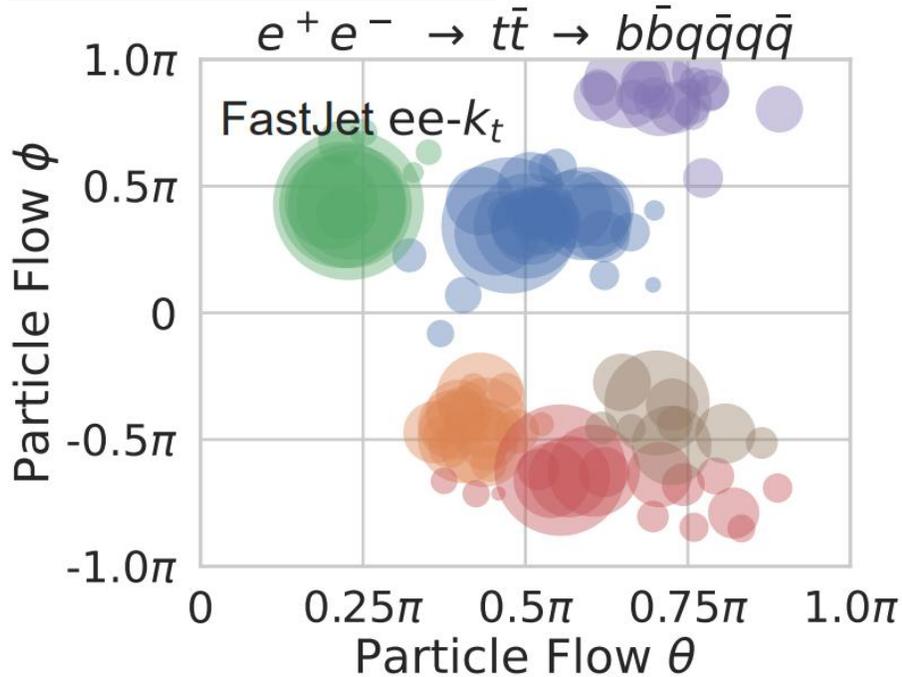
With 1 CPU or 1 GPU (23min → 0.13s)



Data Information		Time to target [s]				
# of particles	QUBO size	bSB	bSB (GPU)	dSB	dSB (GPU)	D-Wave Neal
409	778	0.007	0.021	0.032	0.092	0.060
818	1431	0.012	0.019	0.293	0.478	0.169
1637	2904	0.012	0.019	0.293	0.478	0.169
2456	4675	0.014	0.017	—	—	0.479
3274	6945	0.032	0.022	—	—	1.229
4092	10295	0.005	0.022	0.015	0.065	0.030
4912	14855	0.027	0.016	—	—	2.165
5730	22022	0.109	0.042	—	—	3.853
8187	67570	0.488	0.028	—	—	404.297
8500	78812	1.899	0.108	—	—	785.732
8583	80113	1.321	0.067	—	—	93.782
9435	109498	3.884	0.140	—	—	1366.808

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

Traditional (FastJet)

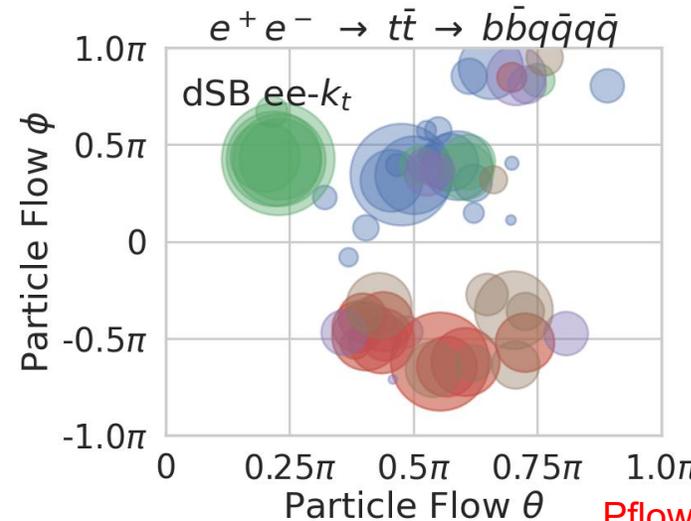
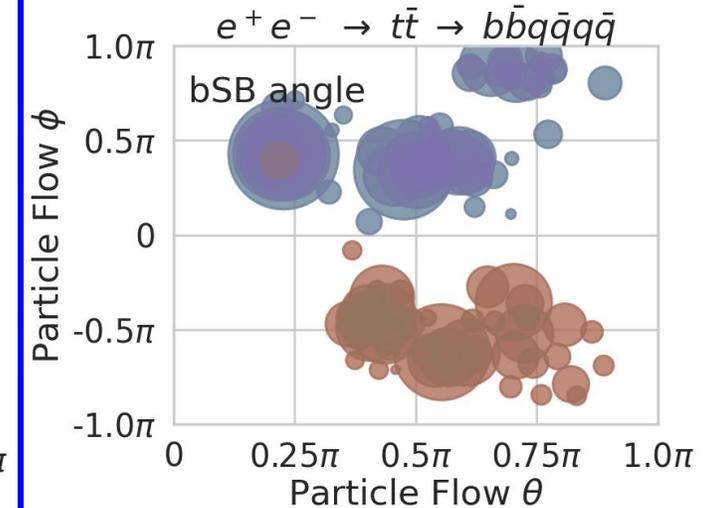
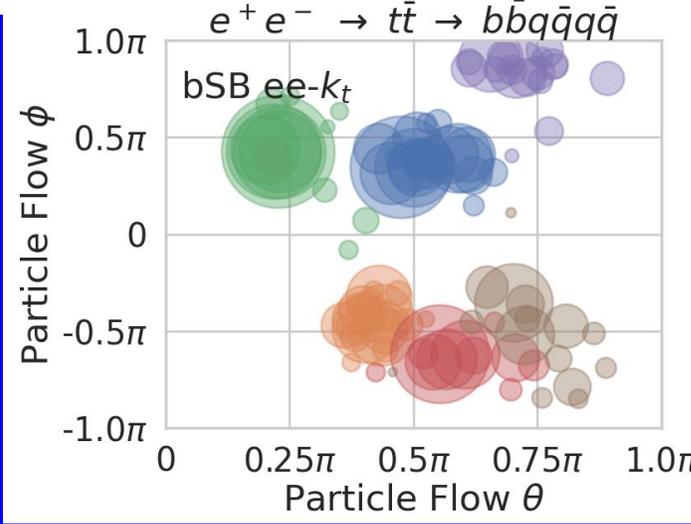


- Only bSB w/ $ee-k_t$ QUBO model can reasonably reconstruct all jets.
- **Angle QUBO model & other quantum-inspired algorithms miss some jets and/or PFlows are totally mixed up.**

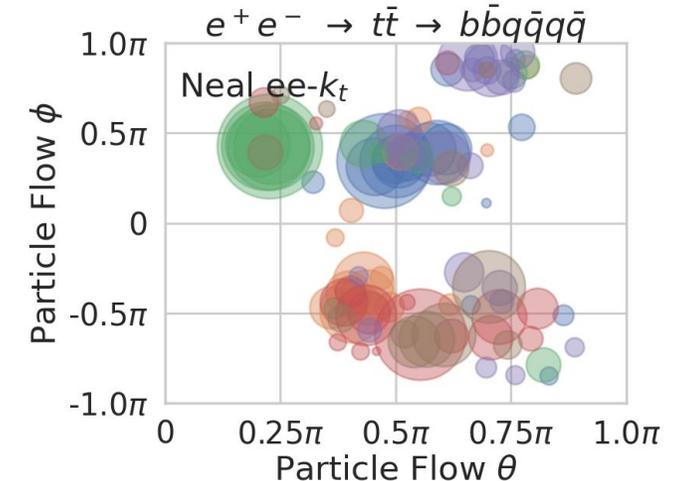
QAIA

Missing some jets + double counting

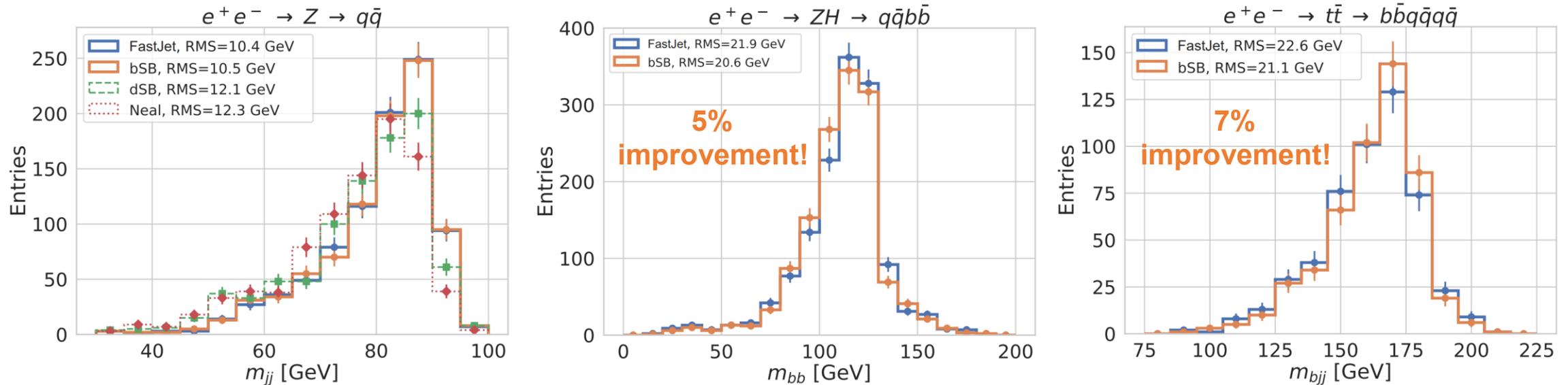
Success!



Pflows totally mixed up



Impact on Invariant Mass



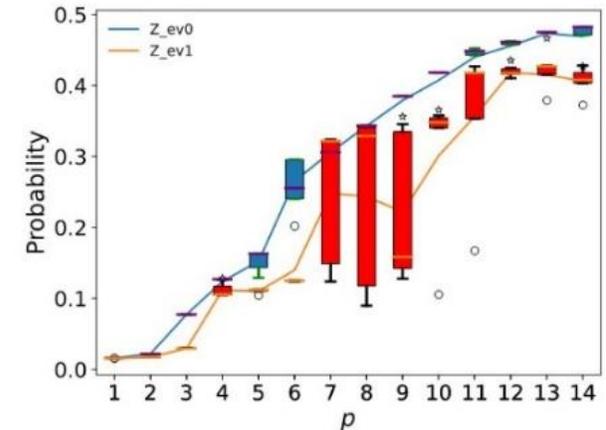
- **The clustering w/ bSB is slightly different from FastJet (see backup for quantitative comparison), but it's OK.** → Let's check the inv. mass resolutions.
- **bSB improve mass resolution for multijet! (& comparable resolution for Z)**
- Other quantum-inspired algorithms (dSB & Neal) already has ~20% degradation in Z mass resolution & unable to properly reconstruct jets in multijet events (thus not shown for ZH & $t\bar{t}$)

Comparison w/ QA & QAOA

- Performance was compared with two simplified datasets (12 qubits) to quantum annealing and QAOA using simulator.
- Even with such small datasets, **bSB exceeds the speed of quantum annealing by about two orders of magnitude & even more for QAOA** (w/ a caveat that it 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 $Z \rightarrow q\bar{q}$ 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