Tracking with Quantum Computers for Future Colliders

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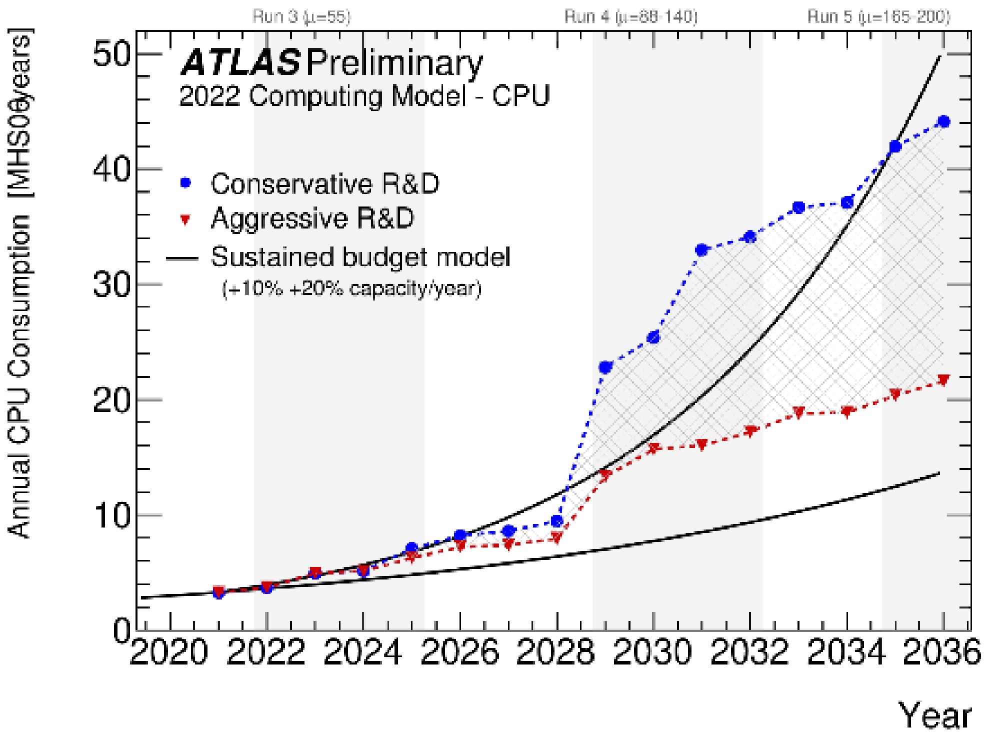
Studies from H. Okawa, arXiv:2310.10255

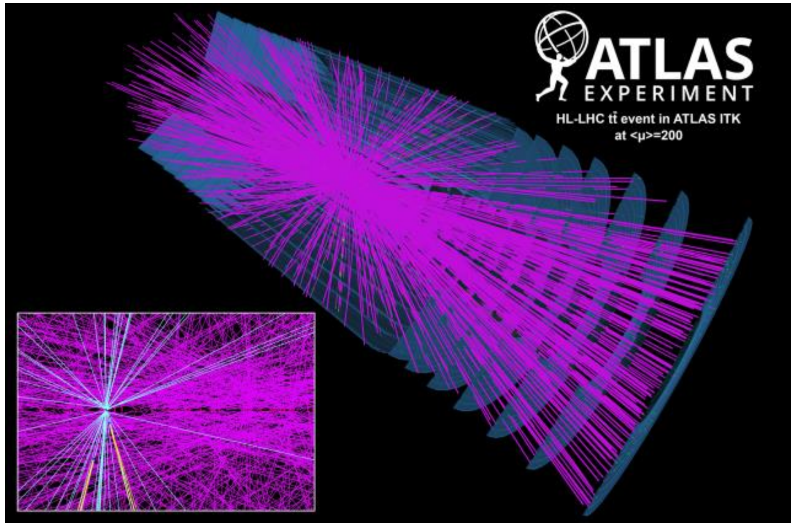
High Luminosity LHC & Beyond



- At the HL-LHC, **we will enter the "Exa-byte" era. Annual computing cost will increase by a factor of 10-20**
- **Without various innovations, the experiment will not be able to operate.** GPUs and other state-of-the-art technologies will be the baseline at the HL-LHC.
- **Quantum computing may bring another "leap".**

- Two of the highly CPU consuming components: **(1) track reconstruction for both data/simulation & (2) simulation of shower development in the calorimeter.** → Xiaozhong Huang will present the latter after my talk.
- **Tackling these challenges will also be useful for other future colliders, such as CEPC & SppC etc.**

Track Reconstruction at LHC & HL-LHC



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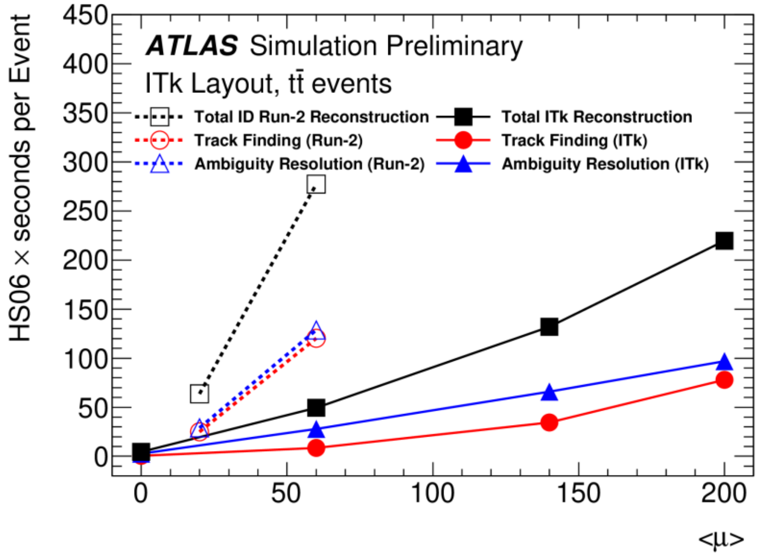
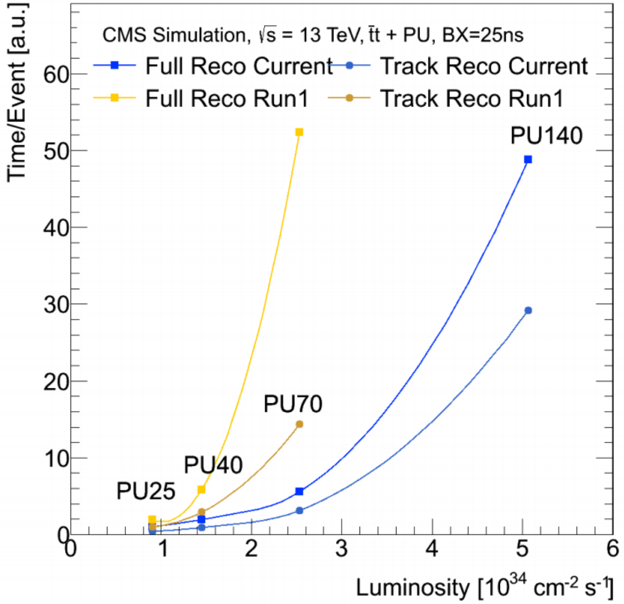


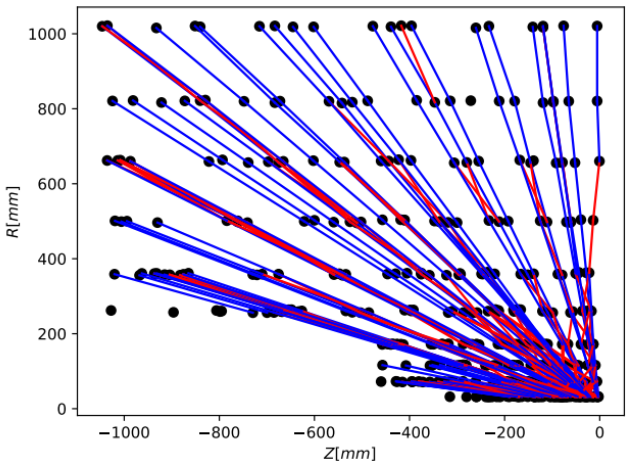
https://cds.cern.ch/record/1966040

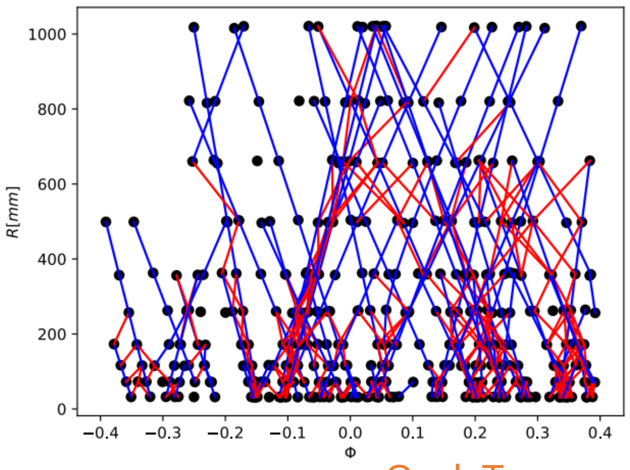


	Run 1	Run 2	HL-LHC
μ	21	40	150-200
Tracks	~280	~600	~7-10k

- At the HL-LHC, additional interactions per bunch crossing becomes exceedingly high & **CPU time blows up with more pileup.**
- GPU & ML-based approaches could be considered as a baseline, but quantum ML may play an important role.

Classical ML Approaches





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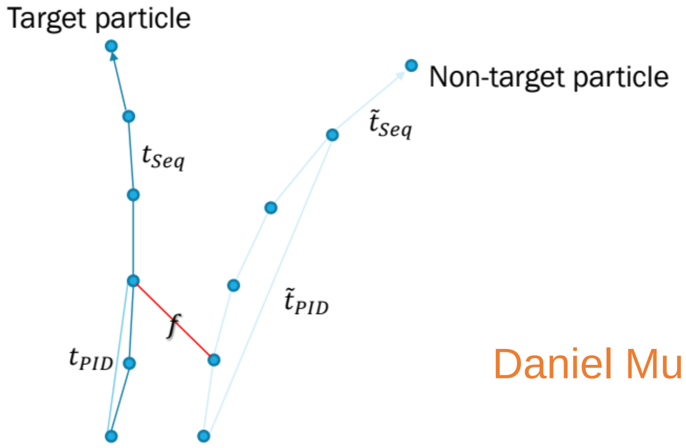
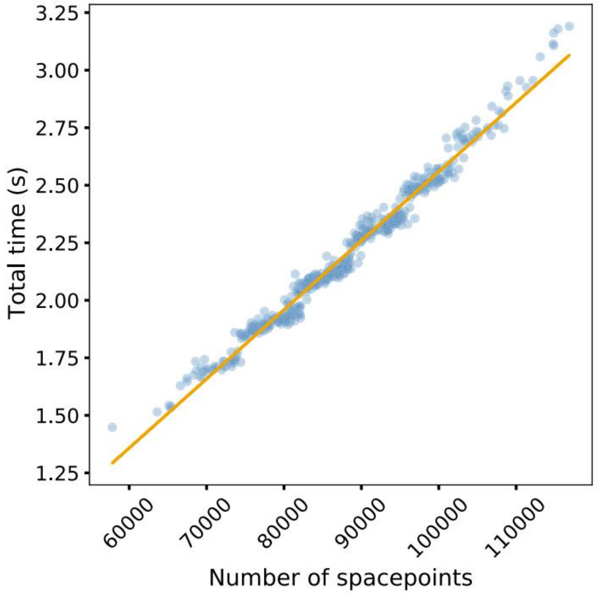
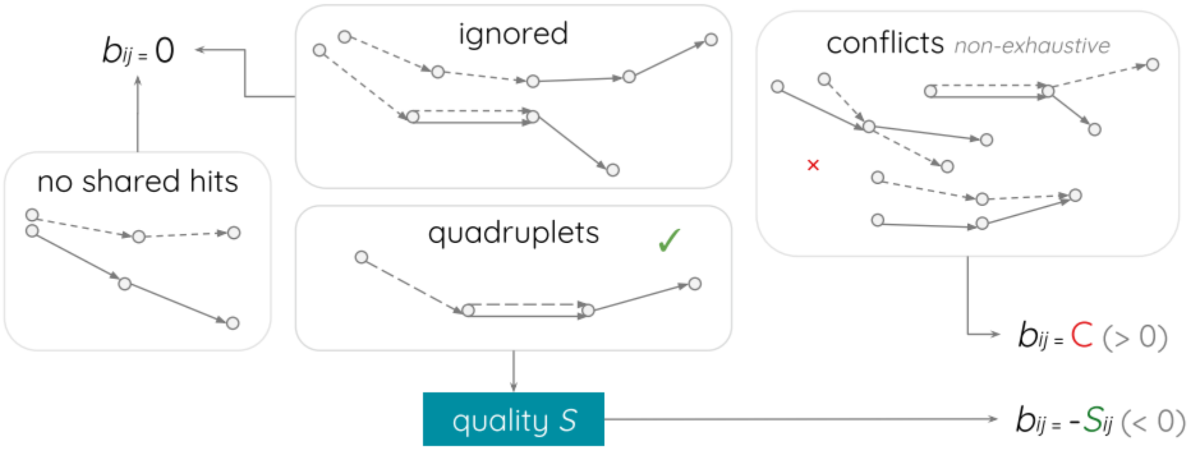


Daniel Murnane

- Graph neural network (GNN) is actively investigated in the LHC [Project Exa.TrkX] & BES-III communities.
  - There are also studies using CNN & Point Net at BES-III
- Silicon hits can be regarded as "**nodes**" & connected segments as "**edges**"
- Computing time scales linearly with number of tracks



Quantum Approach: QUBO



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

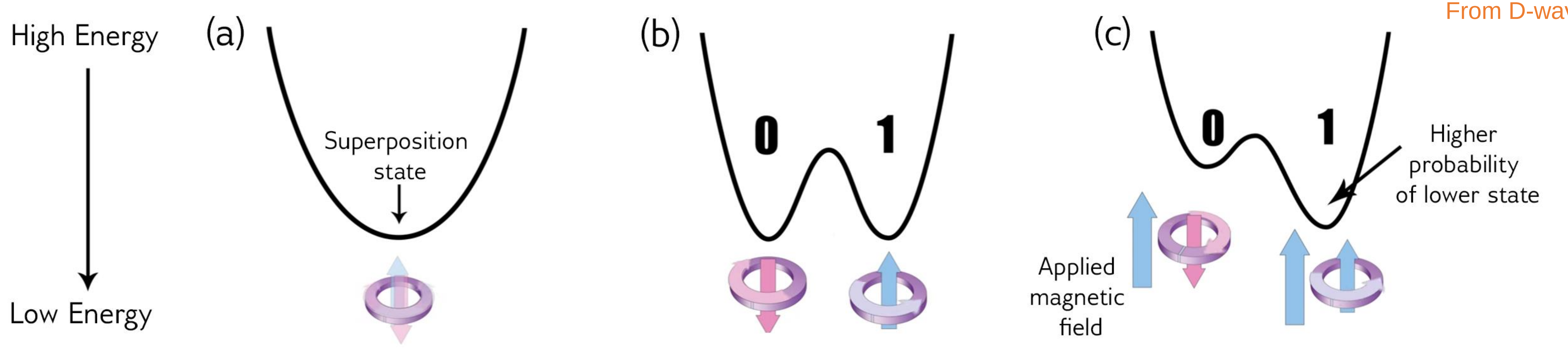
$$O(a,b,T) = \underbrace{\sum_{i=1}^{N} a_i T_i}_{\text{Quality of triplets}} + \underbrace{\sum_{i}^{N} \sum_{j<i}^{N} b_{ij} T_i T_j}_{\text{Compatibility b/w triplet pairs}}$$

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

- Triplets (segments w/ 3 hits) are formed from doublets (segments w/ 2 hits).
- Triplets are used to reconstruct tracks & can be regarded as a **quadratic unconstrained binary optimization (QUBO)** problem. (QUBO matrices for tracking is generally sparse)
- **Minimizing QUBO is equivalent to searching for the ground state of the Hamiltonian.**

Quantum Annealing Approach

From D-wave website

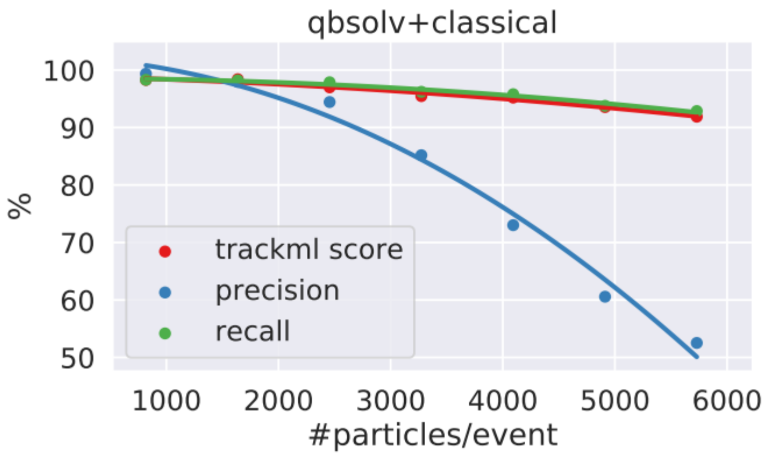


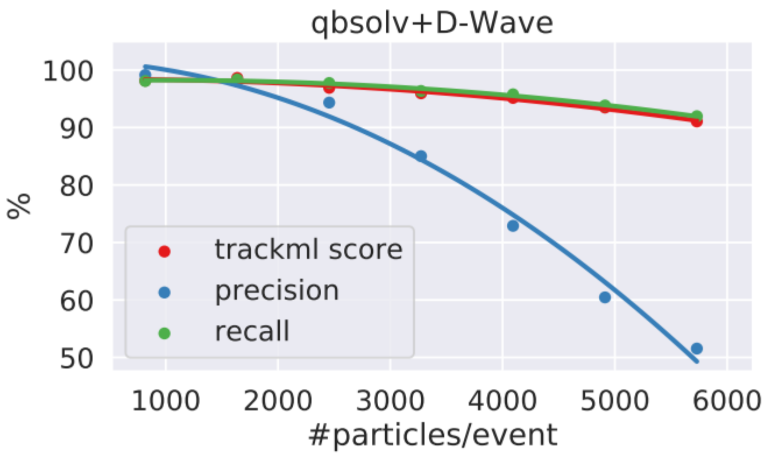
- Quantum annealer looks for the global minimum of a given function with quantum tunneling: a natural machine to search for the ground state of a Hamiltonian.
- D-Wave currently provides 5000+ qubit service (7440 qubits may be available in 2024).
- Pros: High number of qubits available (concept fundamentally different from quantum gates).
- Cons: Can only run QUBO problems. Also, not suitable for very small minimum energy gaps, as the computing time explodes to remain adiabatic.

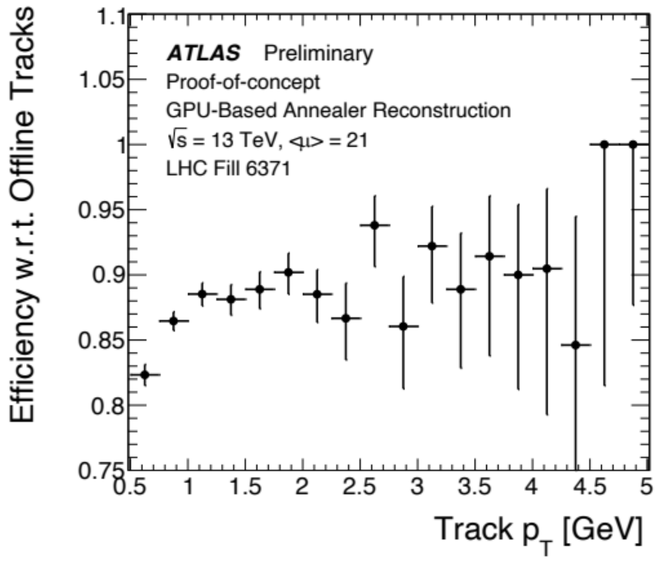
Previous Studies w/ Q. Annealing

- Previous studies w/ 1000-qubit machine show that efficiency is almost stable w/ # of particles, but purity (precision) degrades.
- Simulator provides consistent results w/ hardware!
- There are also ongoing studies in LHC-ATLAS experiment implementing GNN w/ annealers.

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





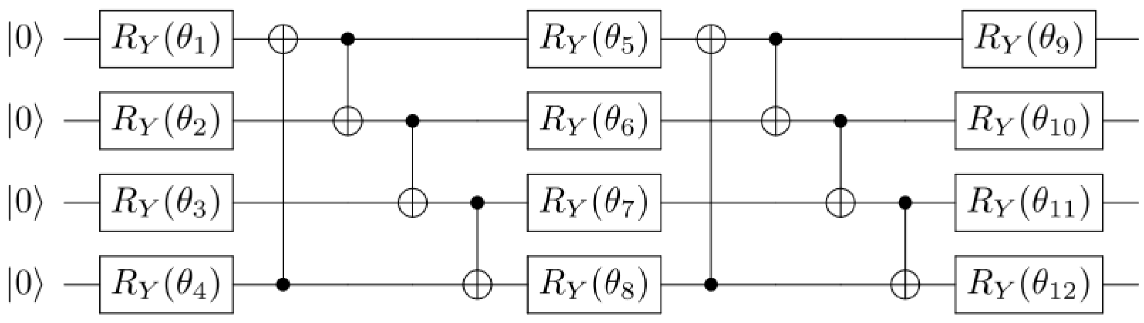


Running on Quantum Gates

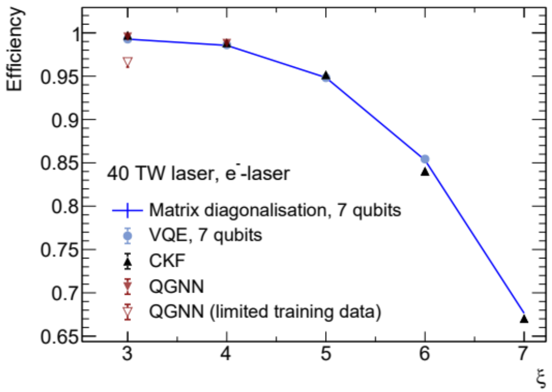
- QUBO can be mapped to Ising Hamiltonian and be solved using Variational Quantum Eigensolver (VQE) or Quantum Approximate Optimization Algorithm (QAOA) w/ quantum gates.

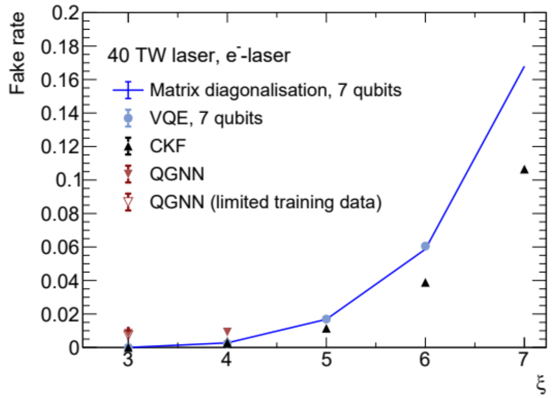
$$\mathcal{H} = -\sum_{n=1}^{N}\sum_{m<n} \bar{b}_{nm}\sigma_n^x\sigma_m^x - \sum_{n=1}^{N}\bar{a}_n\sigma_n^x$$

- Previous LUXE studies considered VQE w/ TwoLocal ansatz w/ R_Y gates & circular CNOT entangling pattern w/ IBM (A. Crippa et al., arXiv:2304.01690, L.Funcke et al., arXiv:2202.06874)
- **QAOA did not perform well & optimization was left for future studies. → A scope of this talk**



Only 4 qubits drawn for simplicity

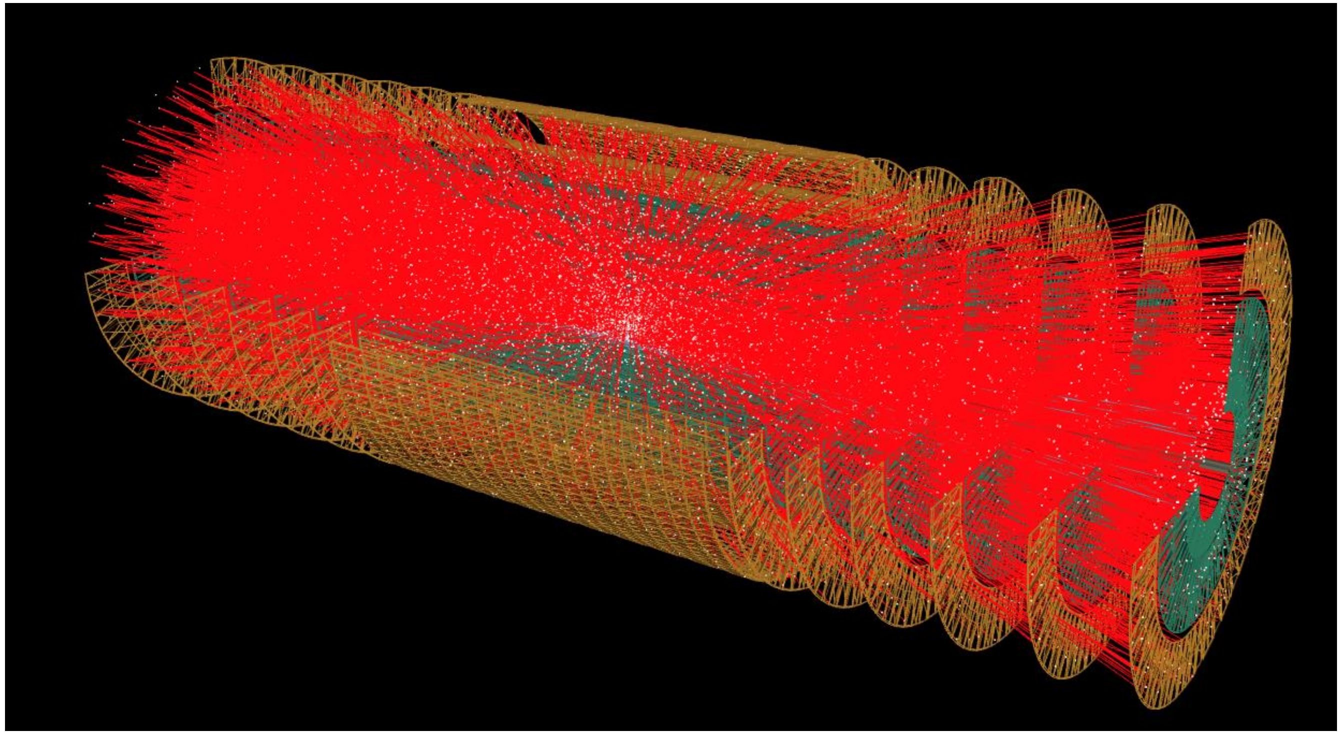




Dataset (TrackML)

- TrackML is an open-source dataset prepared for TrackML Challenges.
- It is designed w/ HL-LHC conditions. It includes noise & holes.
- Continues to be useful for individual studies including quantum tracking.

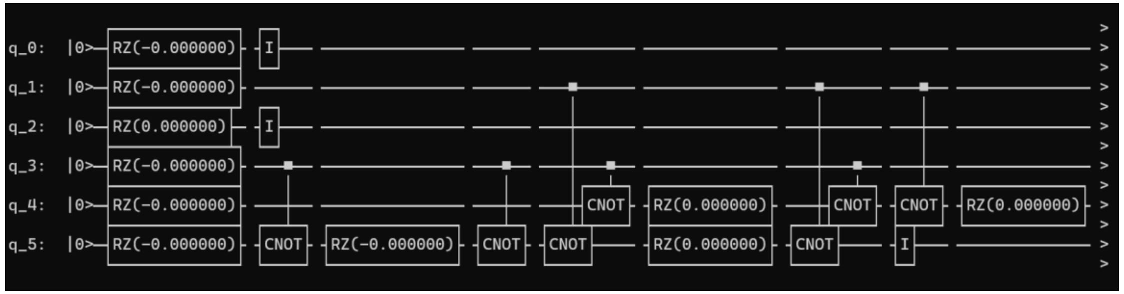
https://www.kaggle.com/c/trackml-particle-identification



Thanks to Andreas Salzburger for suggestions

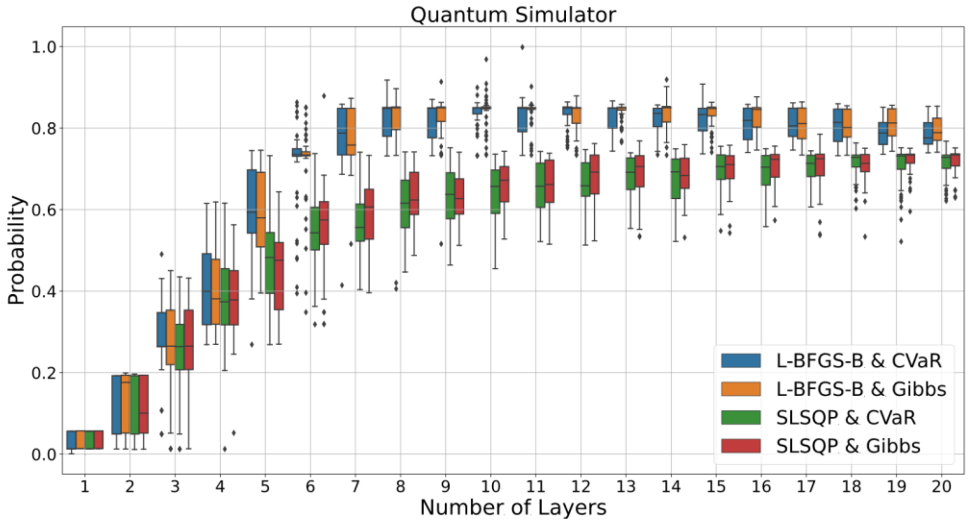
QAOA in Origin Quantum (本源)

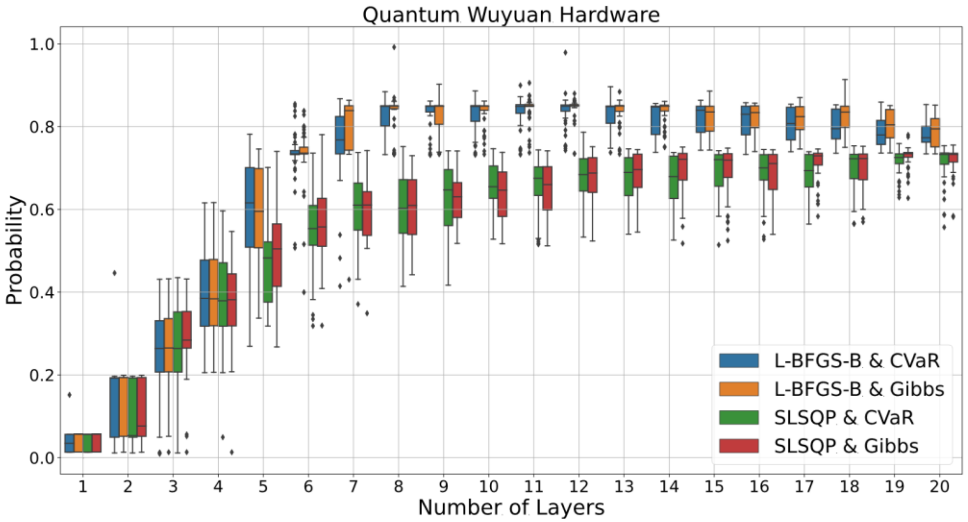
- VQE & QAOA libraries implemented in pyqpanda-algorithm by Origin Quantum (本源).
- Adopts Quantum Alternative Operator Ansatz for QAOA.
- ↓ Conditional Value-at-Risk
  Can utilize CVaR (P. Barkoutsos et al., Quantum, 2020, 4: 256) or Gibbs (L. Li et al., PR Research 2, 023074 (2020)) loss function.
- 6 qubit machine (Wuyuan 悟源) used for the real hardware computation in this talk.



An example of circuits from the actual run

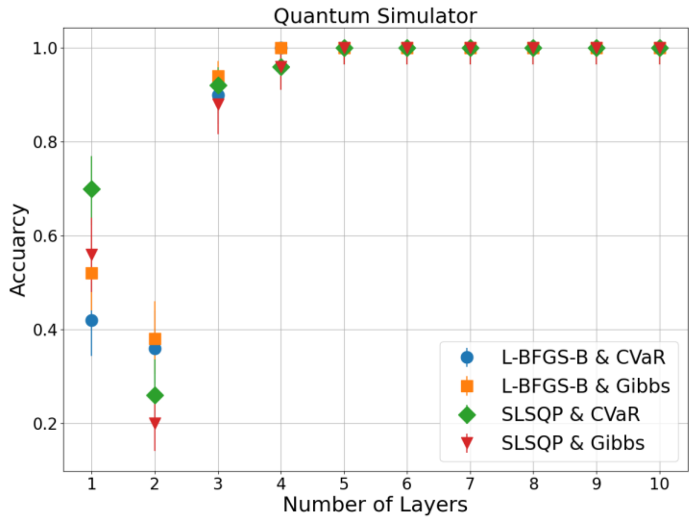
QAOA Optimization

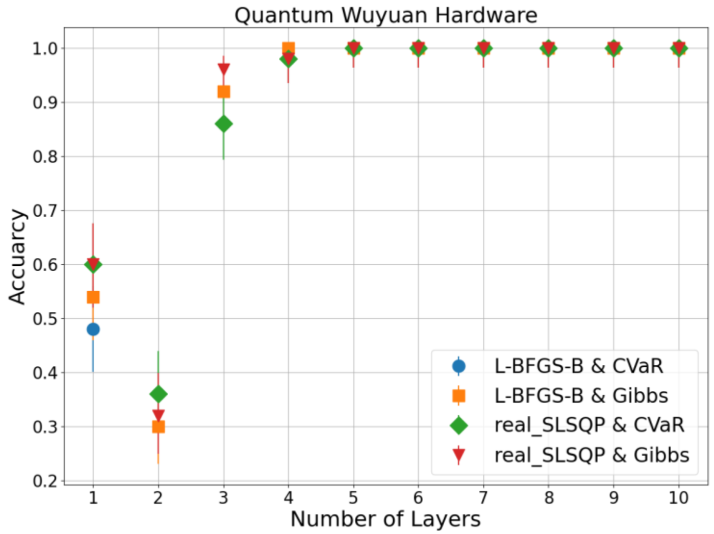




- QAOA does not perform well w/ shallow layers. Compatible performance b/w hardware & simulator.
- L-BFGS-B optimizer is better than SLSQP. TNC has degraded performance & not shown here.
- No significant difference b/w CVaR or Gibbs loss function.
- Probability saturates around 7 layers for L-BFGS-B cases.

QAOA Accuracy

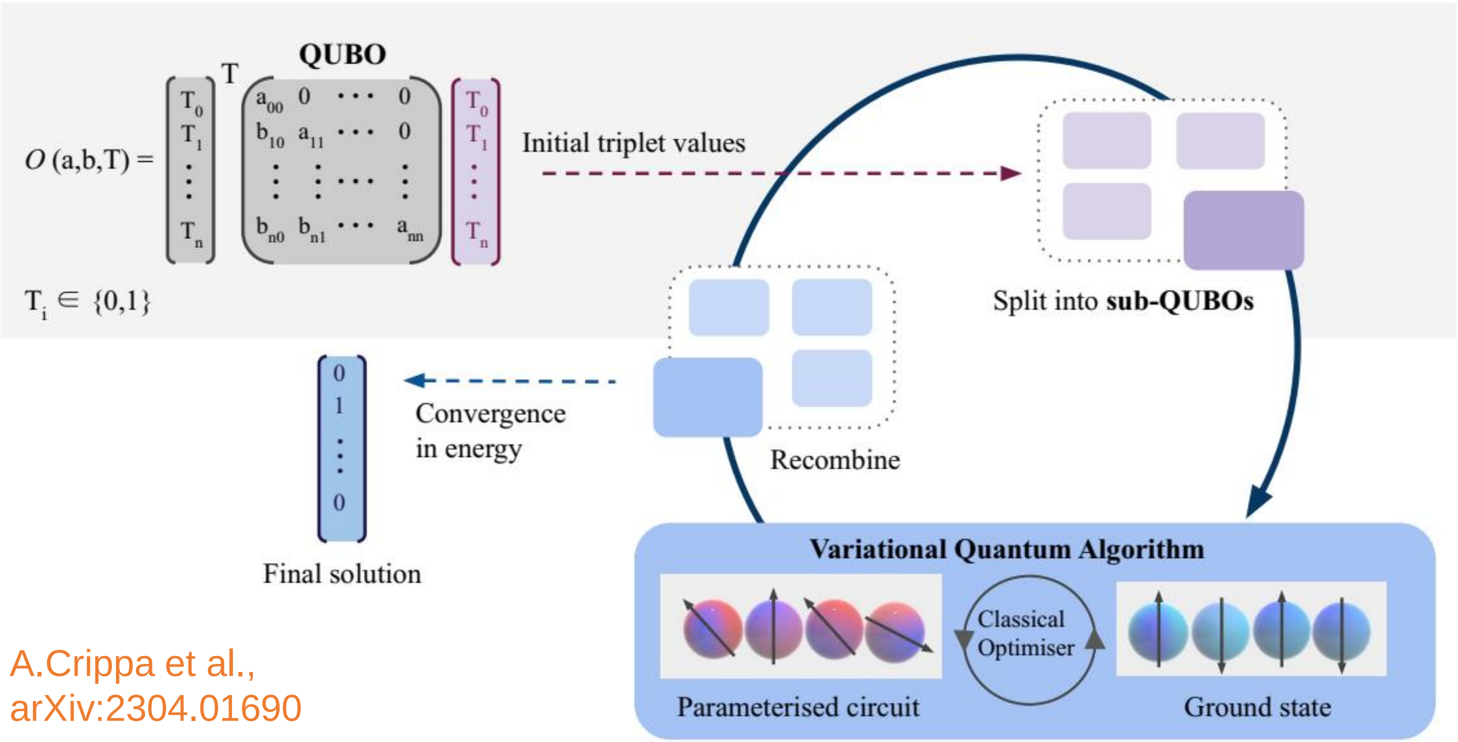




- **<u>Note that the probability is NOT the accuracy of QAOA.</u>**
- A single job runs multiple measurements (or can use the amplitudes for the simulator), ranks the answers by probability & select the highest probability state as the answer.
- The accuracy already reaches 100% within the statistical uncertainty at 5 layers.
- For further studies, a conservative choice of 7 layers is used.

Sub-QUBOs

- **Number of qubits required is determined by the number of triplet candidates** → Obviously cannot cover the full QUBO for tracking in the NISQ era
- QUBO is split into sub-QUBOs of size N (N=7 in previous LUXE studies for IBM machine). **Here, I used N=6 to match with OriginQ hardware.**



A.Crippa et al., arXiv:2304.01690

- There are various sub-QUBO algorithms proposed: qbsolv (now in dwave-hybrid library), for example.
- I adopted a sub-QUBO method using multiple solution instances from Y. Atobe, M. Tawada, N. Togawa, IEEE Trans. Comp. 71, 10 (2022) 2606.

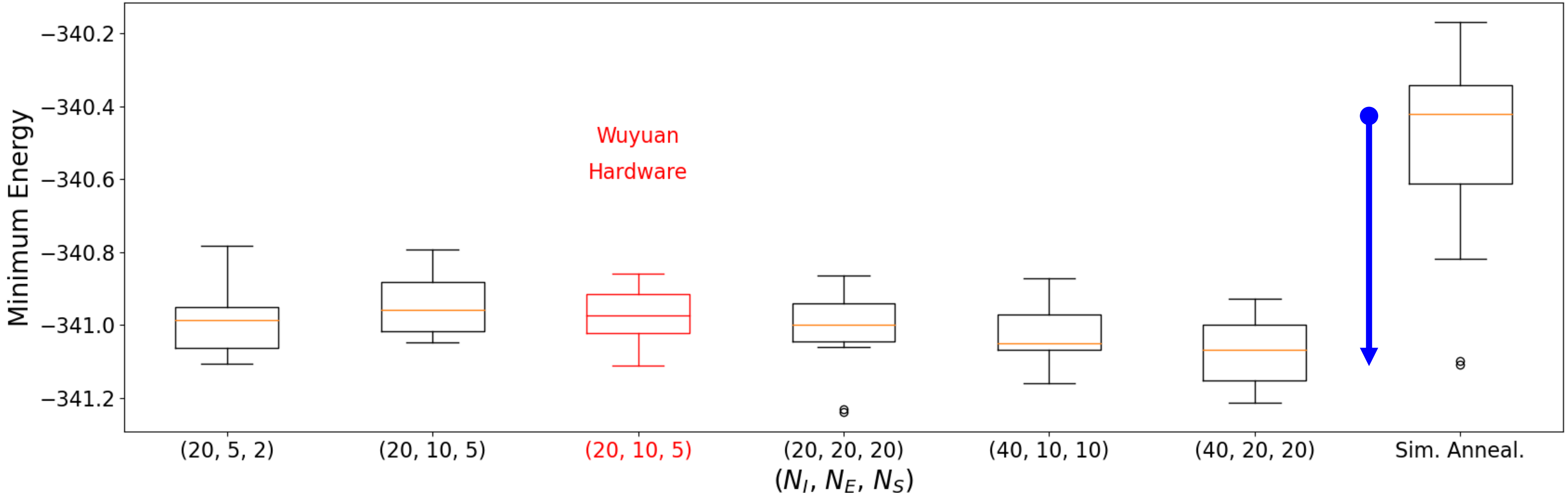
$$QUBO = \sum_{i} a_i x_i + \sum_{i>j} b_{ij} x_i x_j$$

Multiple Solution Instances

- 3 parameters (N_I, N_E, N_S) in this sub-QUBO method.
- Extract N_I quasi-optimal solutions from full-QUBO classically.
- Randomly select N_S solution instances from N_I.
- Focus on particular binary variable x_i. Rank them in accordance to how much they vary over N_S solution instances. Highly varying x_i will be included in the sub-QUBO model.
- Pick-up process of N_S solution from quantum computing is repeated N_E times & N_E sub-QUBO models are considered.
- Returns a pool of N_I solutions & the best solution will be chosen.

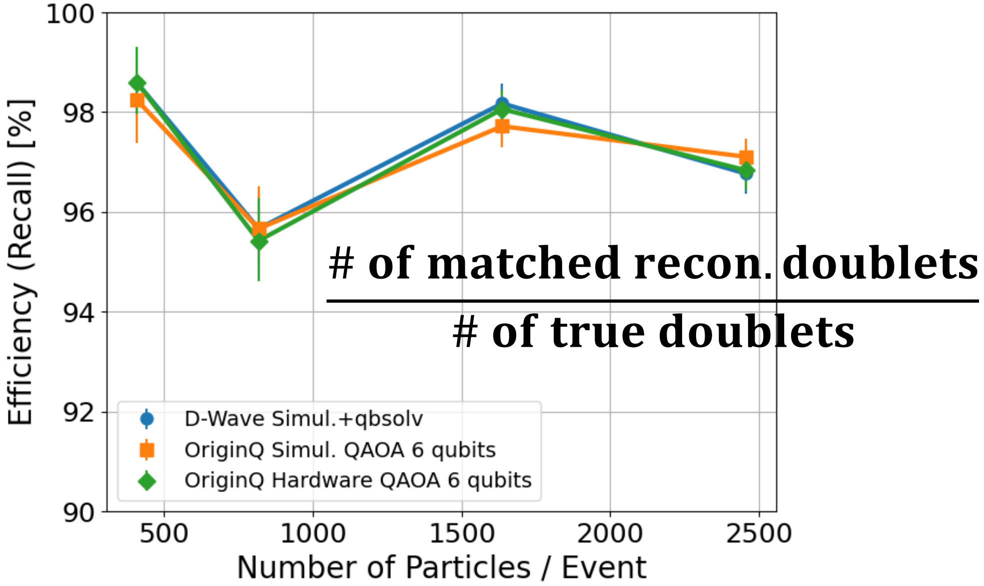
Y. Atobe, M. Tawada, N. Togawa, IEEE Trans. Comp. 71, 10 (2022) 2606

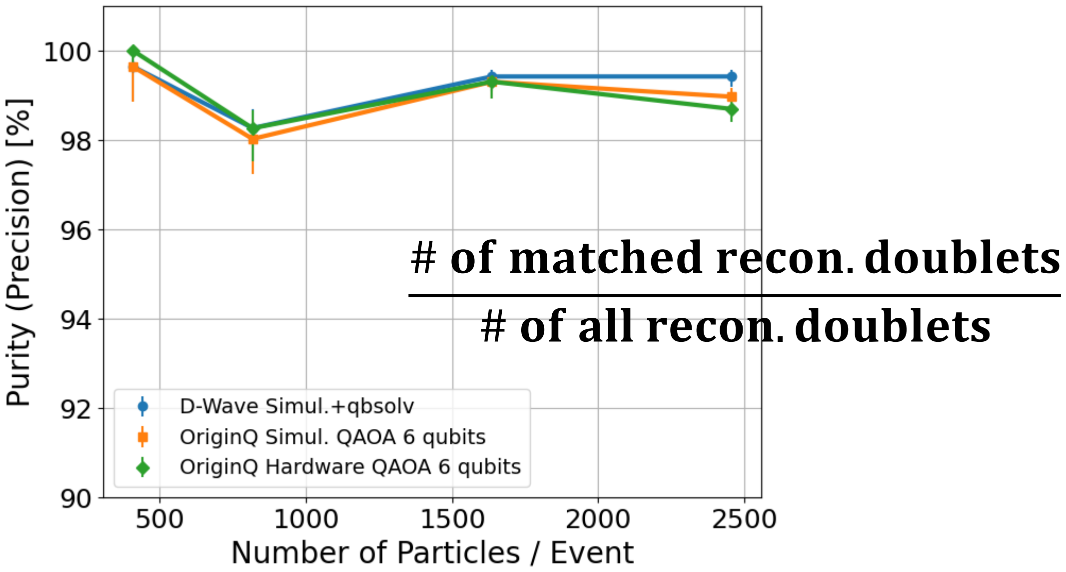
Preliminary sub-QUBO Results



- Ran measurements to compare the performance and stability. 7 layers used in QAOA.
- No significant dependence on (N_I, N_E, N_S) & compatible performance between Origin Quantum simulator & Wuyuan hardware!
- **Visible improvement w/ sub-QUBO compared to the simulated annealing only!**

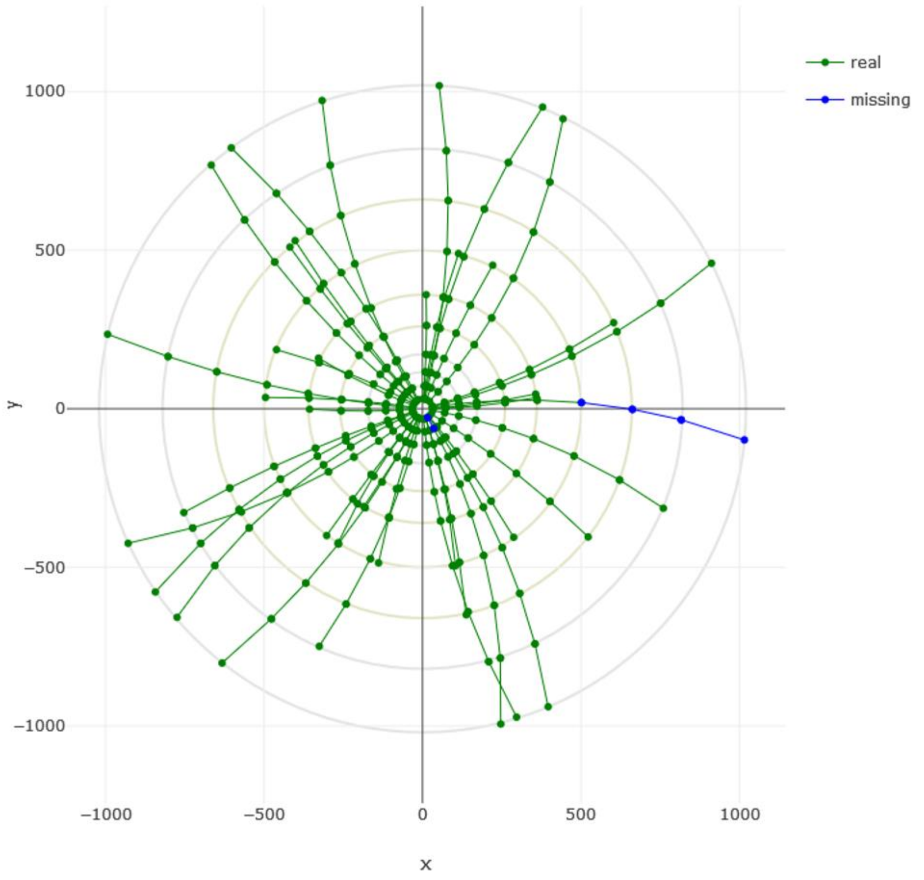
Track Efficiency & Purity

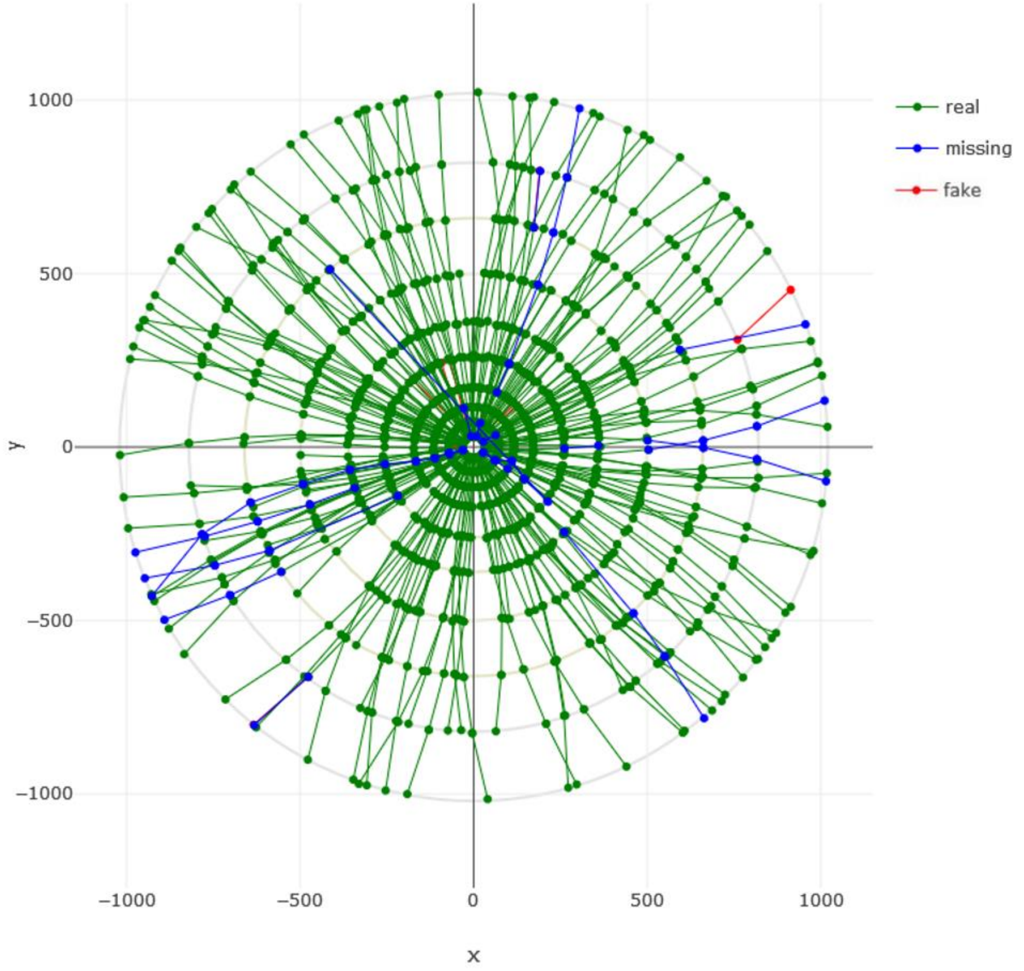




- QAOA+sub-QUBO provides compatible performance as previous quantum annealing studies.
- Fake rate is around 0.01-0.02% throughout.
- No sign of degradation in the Origin Quantum Wuyuan hardware

Event Displays (w/ Wuyuan)





Summary

- Tracking is a highly CPU-consuming task at the HL-LHC era & beyond. Classical ML methods are bringing in promising improvement.
- Another leap from quantum machine learning would be highly exciting.
- Pursued the quantum tracking using Origin Quantum simulator & Wuyuan hardware. The sub-QUBO model + QAOA shows promising performance.
- Further investigations are ongoing. Stay tuned!

谢谢聆听！ Thank you for listening!

Thanks to Federico Meloni & David Spataro for discussions & Origin Quantum (本源) for feedback & computing resources!

Backup

QUBO

H. Okawa, arXiv:2310.10255
& Lucy Linder's Master thesis

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

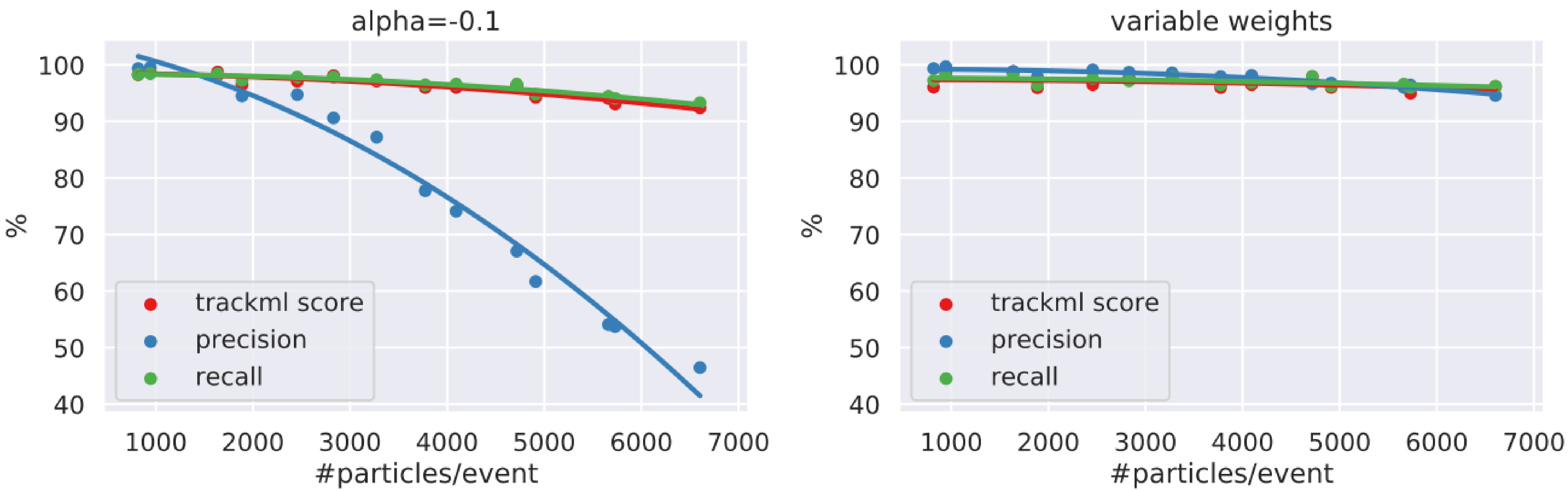
$$S_{ij} = \frac{1 - \frac{1}{2}(|\delta(q/p_{Ti}, q/p_{Tj})| + max(\delta\theta_i, \delta\theta_j))}{(1 + H_i + H_j)^2},$$

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

- b_{ij} = 0 (if no shared hit), = 1 (if conflict), = $-S_{ij}$ (if two hits are shared)
- α, β, γ and λ are tunable parameters, taken to be 0.5, 0.2, 1.0 and 0.5

D-Wave Studies

Lucy Linder’s Master thesis



- Impact of parameters in the bias weights a_i