Quantum annealing algorithms for track pattern recognition

Alex Smith[A], Heather Gray[B], Junichi Tanaka[C], Koji Terashi[C], Lucy Linder[B,D], Masahiko Saito[C], Paolo Calafiura[B], Ryu Sawada[C], Wim Lavrijsen[B], Yasuyuki Okumura[C]

UC Berkeley[A], LBNL[B], UTokyo[C], HEIA-FR[D]

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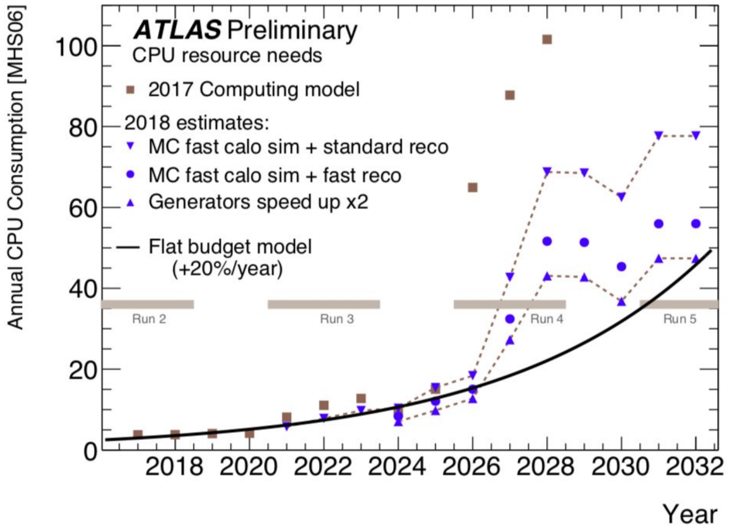
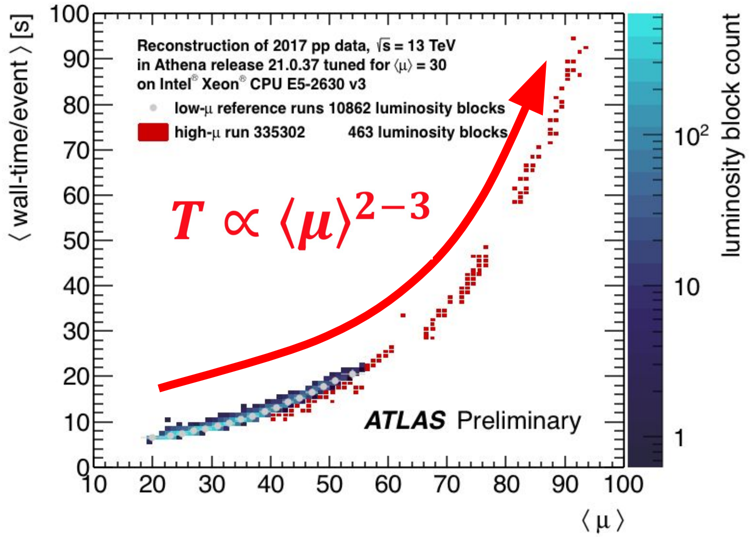
High Luminosity LHC

- HL-LHC coming soon! (2026~)
  - High luminosity ($L = 5{\times}10^{34}\ cm^{-2}s^{-2}$)
  - High pileup ($\langle\mu\rangle = 200$)
  - High readout rate
- CPU consumption will dramatically increase
  - especially track reconstruction due to the high pileup

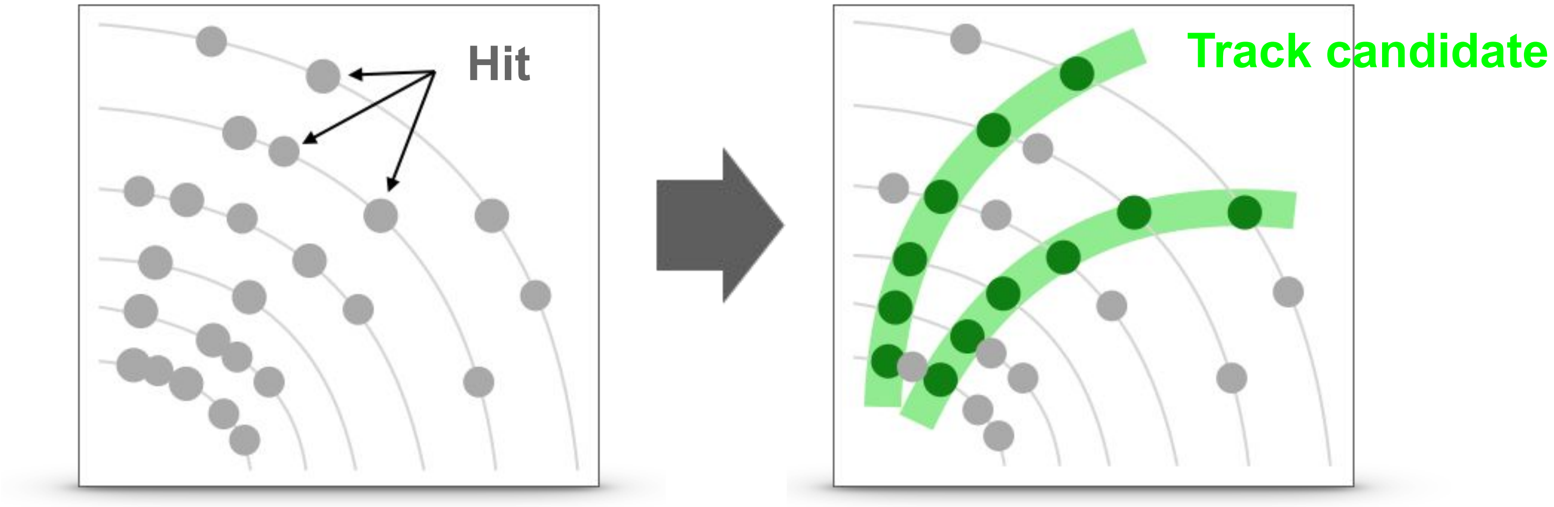
New ideas required





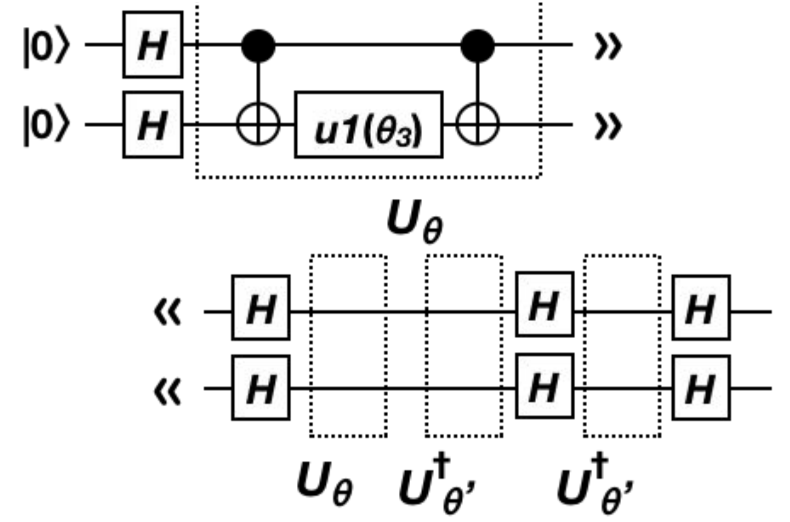
Track reconstruction

- Find the correct set of hits belonging to the same particle
  - Hits are distributed according to known physics rule: helix curve, scattering with material…
- Combinatorial optimization problem
  - HL-LHC environment (<mu>=200)
    - 10^4 particles, ~10 detector layers. i.e. 10^5 hits
  - Does quantum computing favor such a problem?

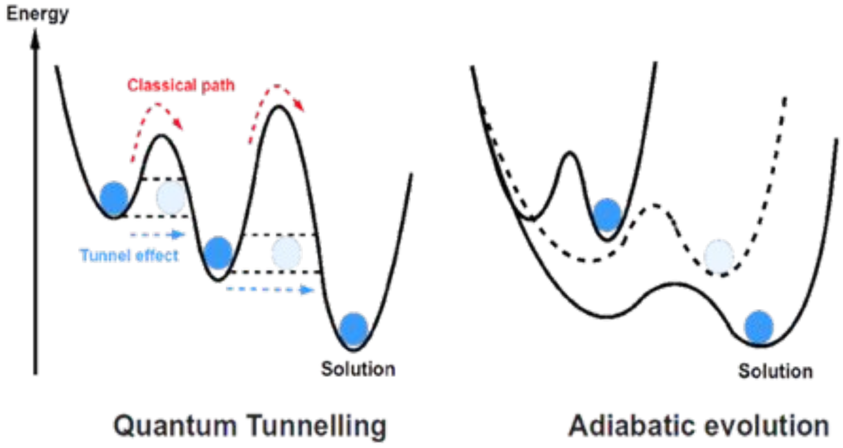


Quantum Computer

Universal quantum circuit



Quantum annealer



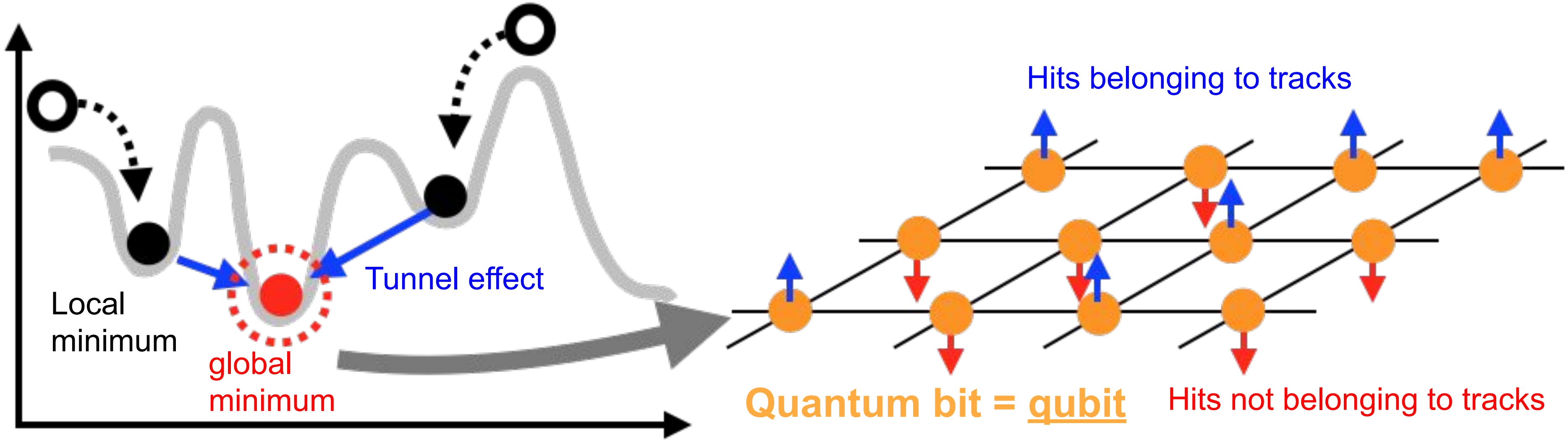
- Arrange gates for each problem
- General-purpose computer

- Find the minimum energy state of a given Hamiltonian
- Suitable for an optimization problem

Focus on quantum annealer

Quantum annealing

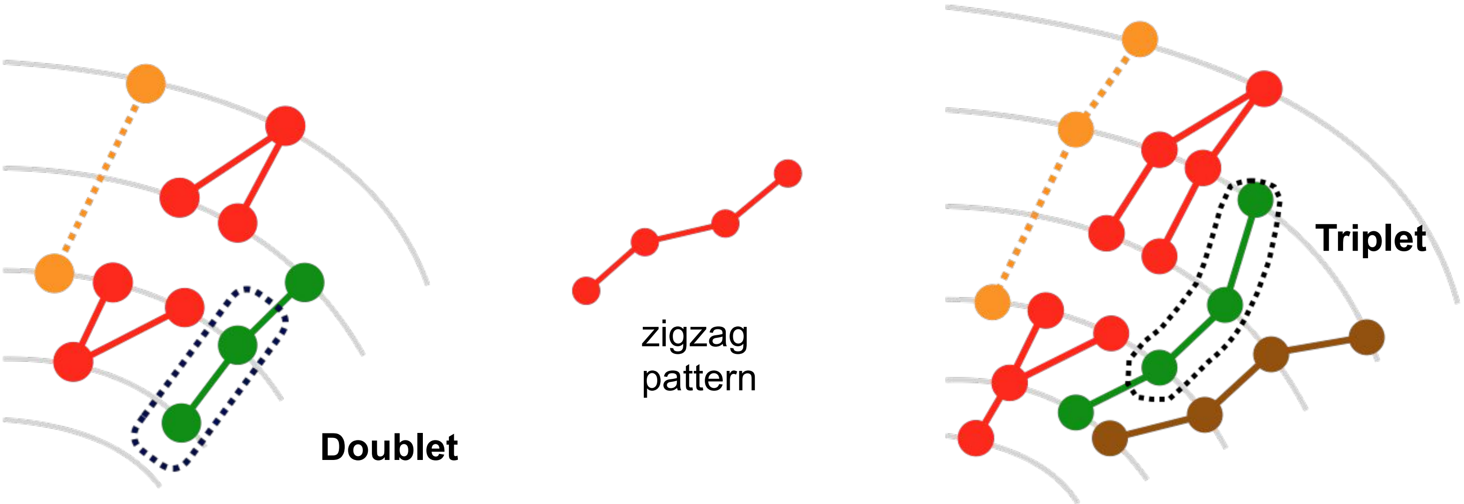
- Construct Hamiltonian taking minimum energy at a target state
- Start with the superposition of all possible states under an external transverse B-field, then move to the optimal state.



- What is the best assignment for qubit?
- How is Hamiltonian designed?

Qubit assignment

- Doublets
  - Original paper (Stimpfl-Abele, et. al., 1991)
  - Zigzag pattern, many qubits required due to many possible fake candidates
- Triplets
  - This work (arxiv: 1902.08324)
  - Strong fake reduction, resulting in a reasonable number of qubits



Hamiltonian

$$E = \alpha\left(\sum_{i}^{N} T_i\right) - \left(\sum_{i,j} S_{ij} T_i T_j\right) + \zeta\left(\sum_{i,j} T_i T_j\right), \quad T \in \{0,1\}$$

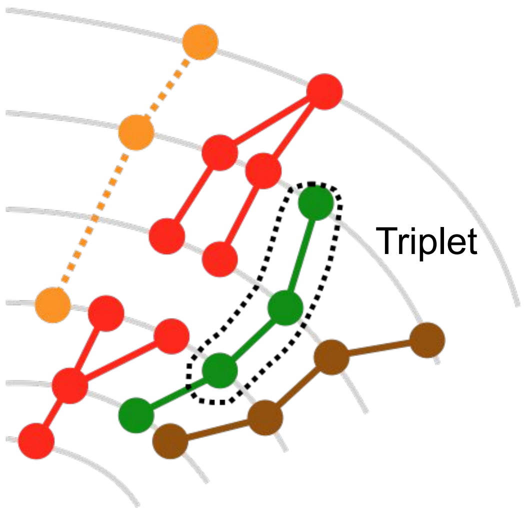
qubit

bias weight Connection strength Avoid conflicts, zigzag pattern, holes

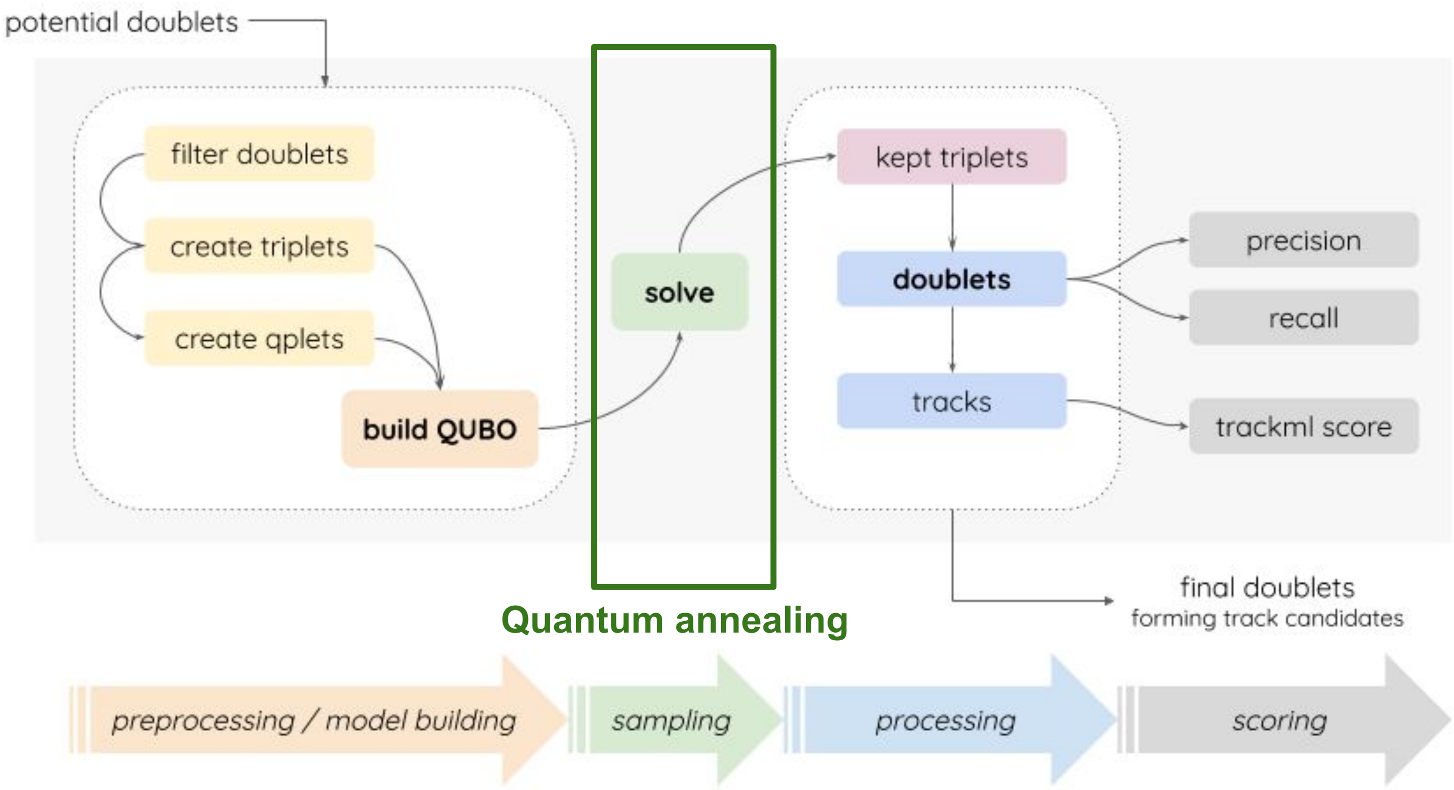
Quadratic Unconstrained Binary Optimization (QUBO)

$$O(a,b,T) = \sum_{i}^{N} a_i T_i + \sum_{i}^{N} \sum_{j<i}^{N} b_{ij} T_i T_j \qquad T \in \{0,1\}$$

$$b_{ij} = \begin{cases} -S(T_i, T_j) \\ \zeta \\ 0 \end{cases}$$



Overview



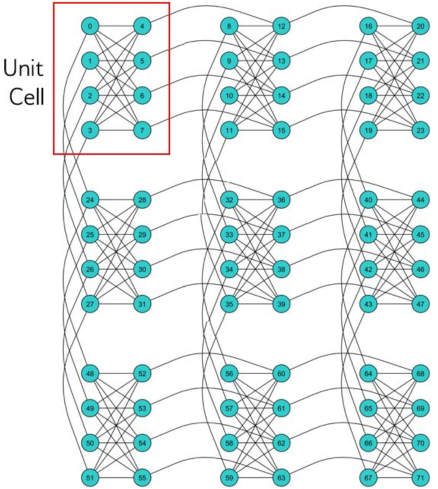
HEPQPR.Qallse: https://github.com/derlin/hepqpr-qallse

D-Wave Quantum Annealing Machine

D-wave 2000Q

- Superconducting qubits (cool down to 15 mK)
- 2048 qubits (D-wave 2000Q)
- Chimera graph
  - 16x16 units, 8 qubits / unit
    - 6016 couplers
  - ~ 64-bit full connection
- Annealing time 1-2000 μs

Chimera graph

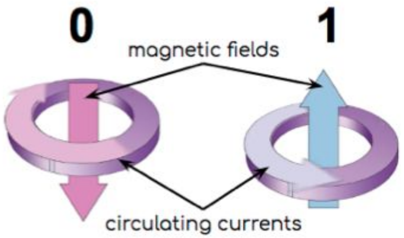


Next-generation machine:

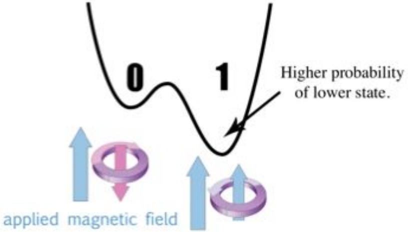
- Pegasus processor
- 5000 qubits
- 2020 mid

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

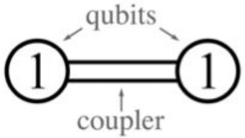
qubit: T_i



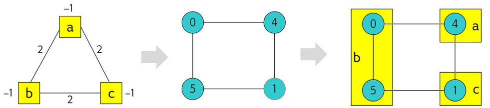
bias weight: a_i



coupling strength: b_{ij}

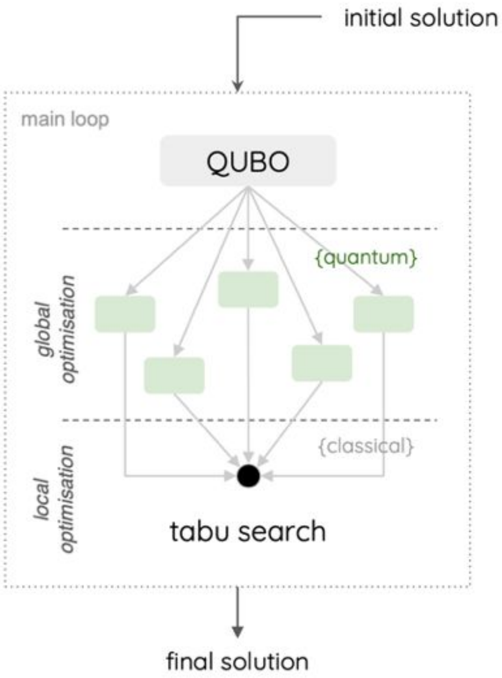


Minor embedding

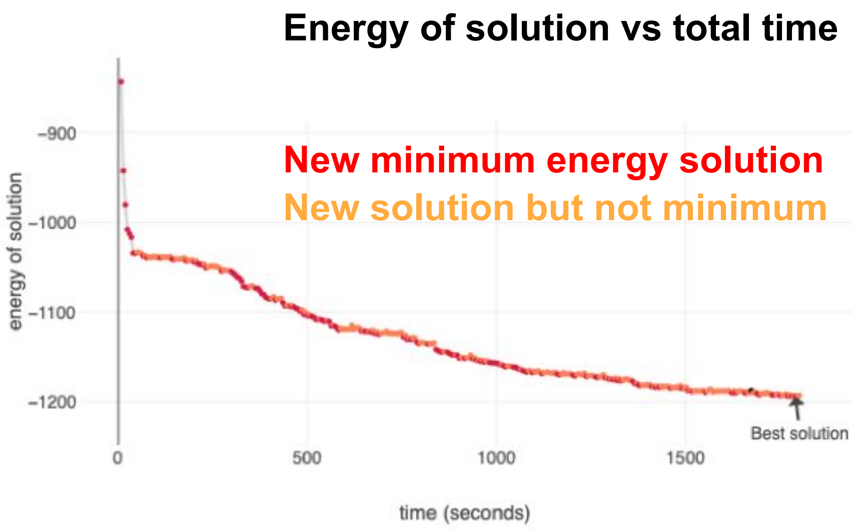


Solving

- Large QUBOs split into sub-QUBOs due to limited number of qubits
  - Solve each small QUBOs using D-wave hardware
- Repeat annealing to guarantee an optimal solution



4900 particles (60% of HL-LHC)



Construct track candidates using doublets in final triplets

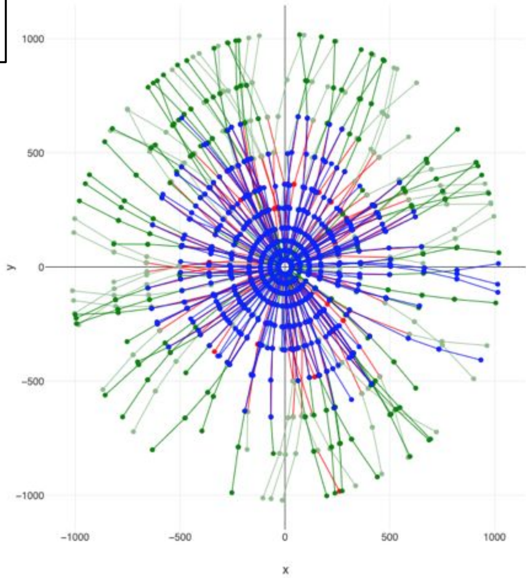
Results

Reconstructed high pT tracks
Reconstructed low pT tracks
Not reconstructed tracks
Fake tracks

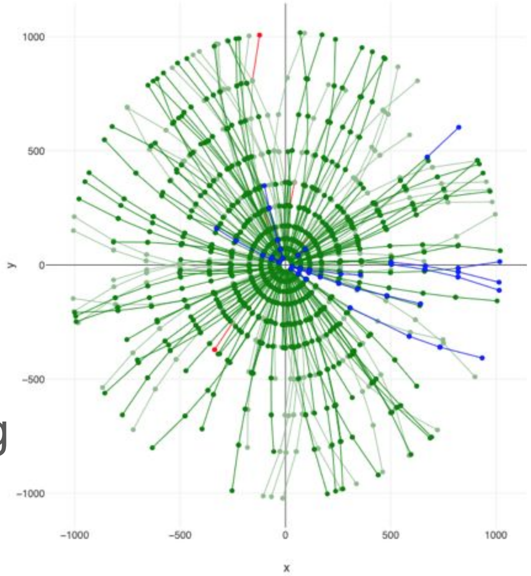
1600 particles (20% of HL-LHC)
- 11000 hits

Input

Doublet selection



Annealing

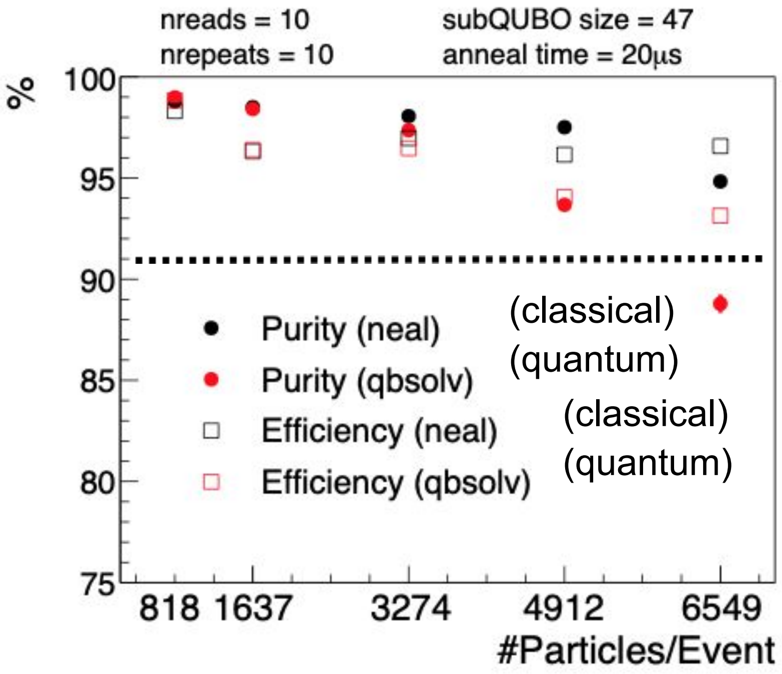


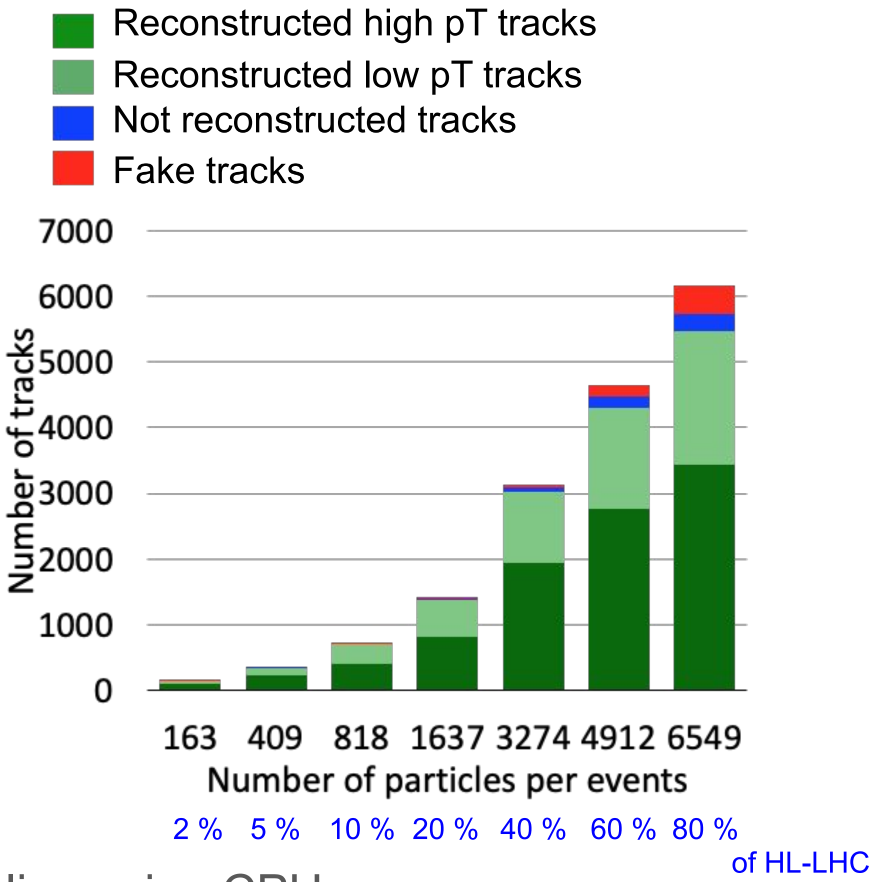
390000 Doublets	
Purity	0.22 %
Efficiency	99.5 %

2445 Doublets

1424 Doublets	
Purity	98.5 %
Efficiency	96.4 %

Results





- Reference solver: neal = simulated annealing using CPU
- >90 % efficiency / purity below 6000 particles environment
- Equivalent performance with the classical annealing (neal)

Digital annealing

- Aiming to larger & easier-to-use annealing device
  - Limit from QUBO size at tracking
- Is a digital annealing a candidate?
  - simulated annealing using logic circuits on a chip
- Fujitsu Digital annealer
  - Anneal by artificial fluctuation
  - Work at normal temperature, no quantum noise
  - 8192-bit full connection (2nd generation chips)
  - precision of weight in QUBO: 64 bit
- We've demonstrated our track finding algorithm with the 1st generation chips (1024 qubits)
  - Equivalent performance with the classical annealing algorithm (neal)
  - Results are stable
  - Annealing time: 0.5 sec (depends on problem sizes)
    - ~4sec for CPU pre/processing

Summary

- HL-LHC poses a **significant challenge to computing**
  - especially track reconstruction
- One of the new ideas is **quantum annealing**
- Hamiltonian and QUBO are constructed based on triplet as qubits.
- Successful results for quantum annealing using **D-wave machine and Fujitsu digital annealer**
- Future work
  - QUBO Optimization
    - Optimize the coupling strength, bias term, conflict term,...
    - Other qubits: quadraplet, doublet, hit,...
  - Comparison between different devices
    - D-wave
    - Digital annealer (Fujitsu, Hitachi, …)