Applied Quantum Annealing for Track Reconstruction in HEP

Parker Reid
WNPPC February 2019

ATLAS EXPERIMENT

SFU SIMON FRASER UNIVERSITY

D-Wave The Quantum Computing Company™

Motivation:

HL-LHC scheduled to operate by 2027

- Bunch crossing factor of 3 greater than Run 3

Tracking algorithms functioning with high precision and efficiency

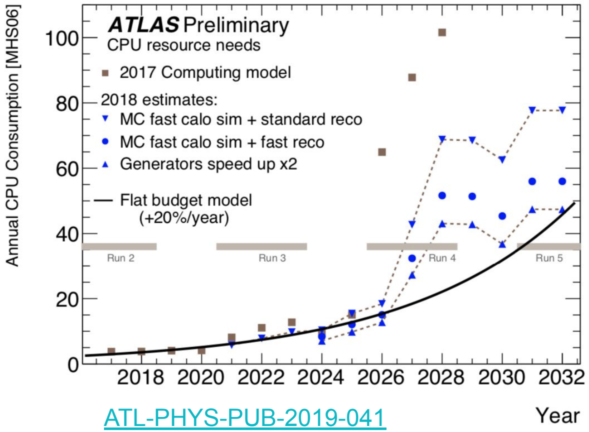
- **CPU intensive**
- Time-saving algorithms valuable

D Wave: Quantum Annealing (QA) hardware company based in Burnaby BC

- Alternative computing paradigm

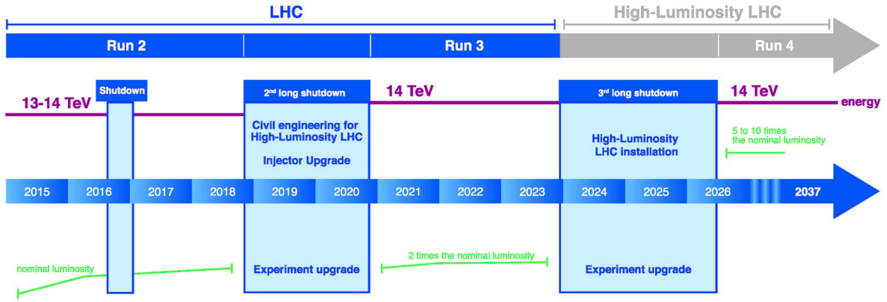
Goal: Develop further understanding of QA in tracking algorithms in High-Energy Physics (HEP)

Software package:HEPQPR/Qallse
Quantum algorithm Lucy Linder 2019



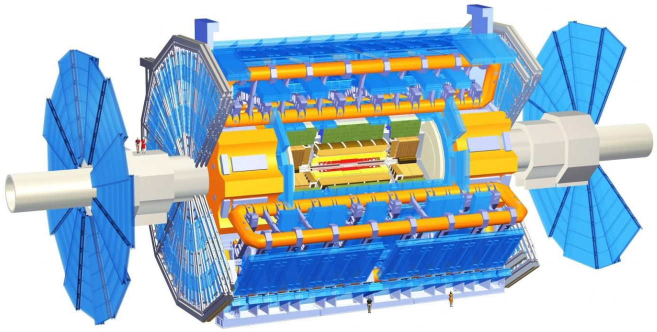
ATL-PHYS-PUB-2019-041

LHC/ High-Luminosity LHC timeline



Tracking: HEP Introduction

Source: ATLAS Experiment© 2014 CERN



Detector:

- Cylindrically symmetrical
- Composed of layers
- Particle interactions with layers recorded as "**Hits**"

Hits → Multiple hit seeds → Tracks

Dataset:

TrackML challenge (2019)

Event data:

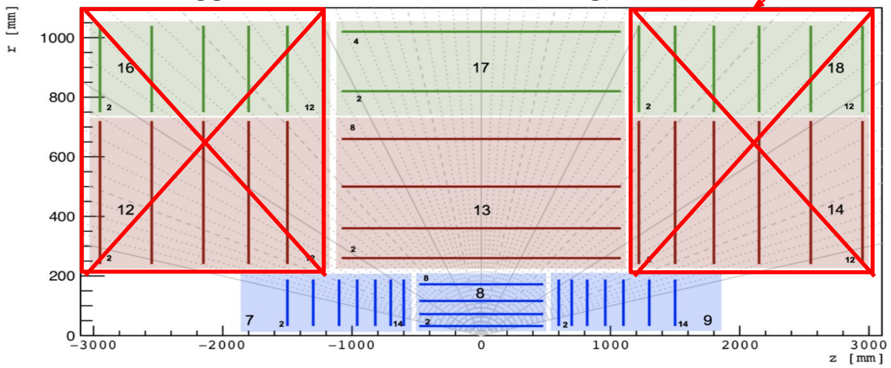
- ~11,000 Particles/event
- ~110,000 Hits/event

Simplifications

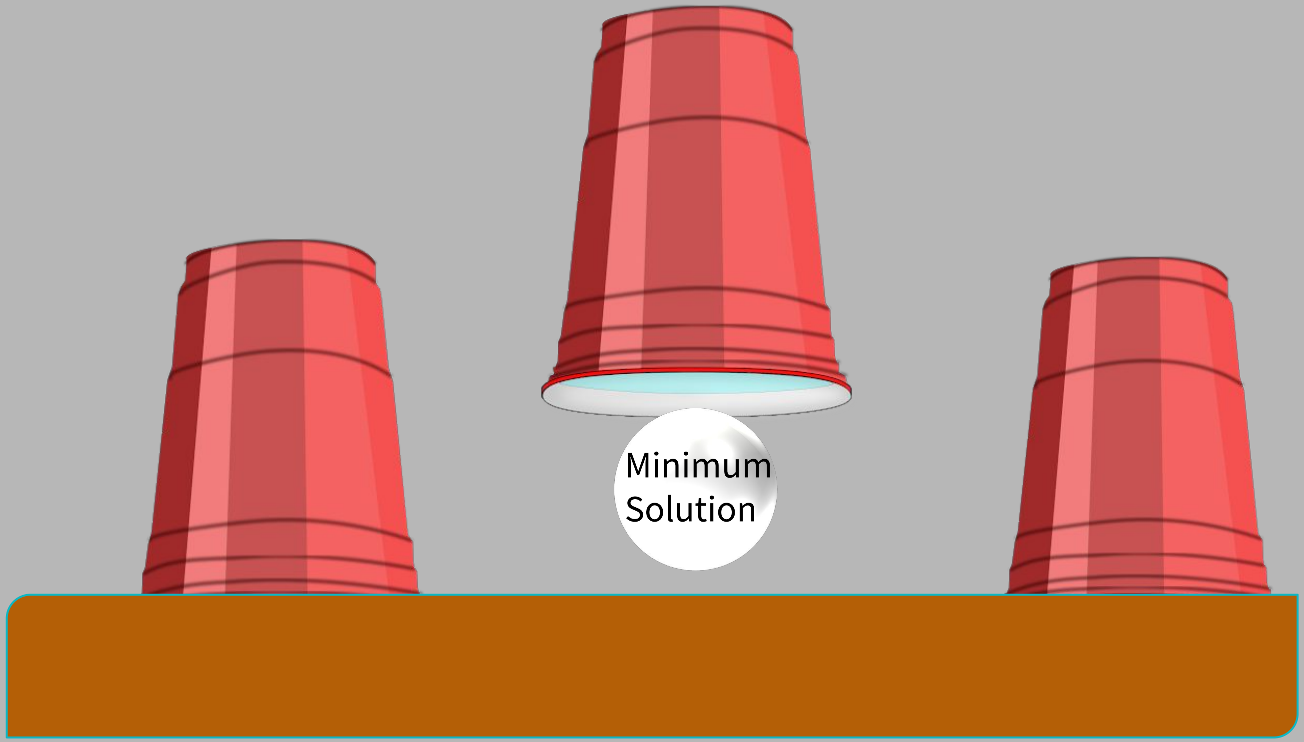
- End-caps removed
- No Calorimeter data

End-Caps removed

Kaggle TrackML Detector Topology: R-Z plane



Crash Course: Quantum Annealing



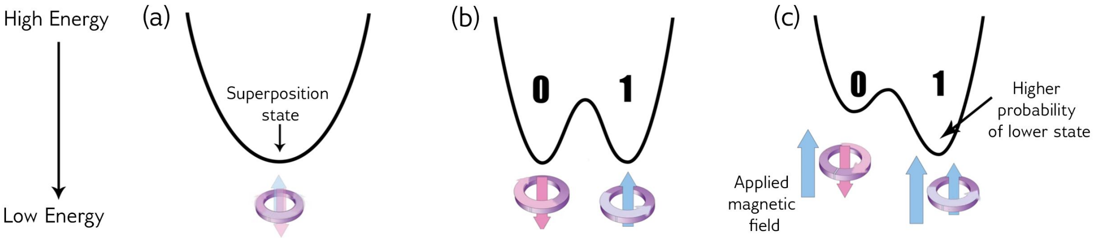
Annealing: Theory

Goal: Find the minimum solution to a complicated function

Quantum Annealing: **Adiabatic Evolution**

Quantum Annealing:

- Hamiltonian represents function
- Starts in known ground state
- Adiabatically introduce function
- Hamiltonian remains in ground state
- Measure state, retrieve solution



Olivia Di Matteo Triumf QM lecture series 2019

$$H_p = -\sum_{i<j} J_{ij}\sigma_i^z\sigma_j^z - \sum_i h_i\sigma_i^z$$

Quadratic **U**nconstrained **B**inary **O**ptimization (QUBO) Problems

- Forms a Hilbert space
- Function minimum solvable by Binary inputs
- Generating best coefficients J_{ij}, h_i non-trivial

Quadratic terms:
- Coupling values within Quantum Annealer

Linear terms:
- Individual nodes within Quantum Annealer

Annealing: QUBO Problems and D Wave

Olivia Di Matteo Triumf QM lecture series 2019

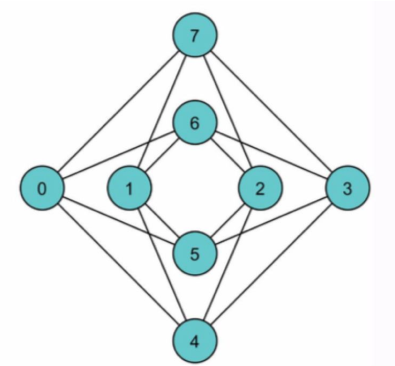
Quadratic **U**nconstrained **B**inary **O**ptimization (QUBO)

$$H_p = -\sum_{i<j} J_{ij}\sigma_i^z\sigma_j^z - \sum_i h_i\sigma_i^z$$

Quadratic terms:
- Node couplings in D Wave

Linear terms:
- Magnetic fields in D Wave
- Act on individual nodes

QMI



D Wave Chimera Structure Schematic

D Wave Hardware:

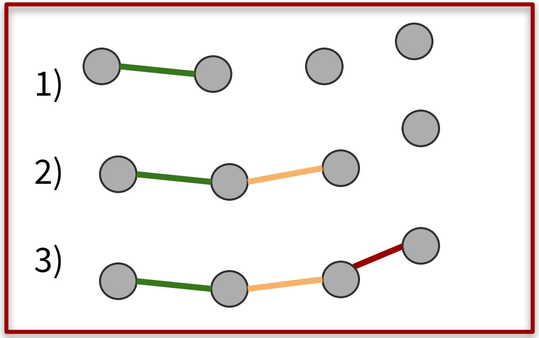
- ~2000 size QUBO QPU on cloud (Chimera)
- 6 Unique connections for each node
- Increase connections at cost of QPU size (Minor Embedding)
- Problem is too large → **QBsolv** algorithm used

Algorithm: Summary

Frederic Bapst et.al., A Pattern Recognition Algorithm for Quantum Annealers. https://doi.org/10.1007/s41781-019-0032-5. (2019)

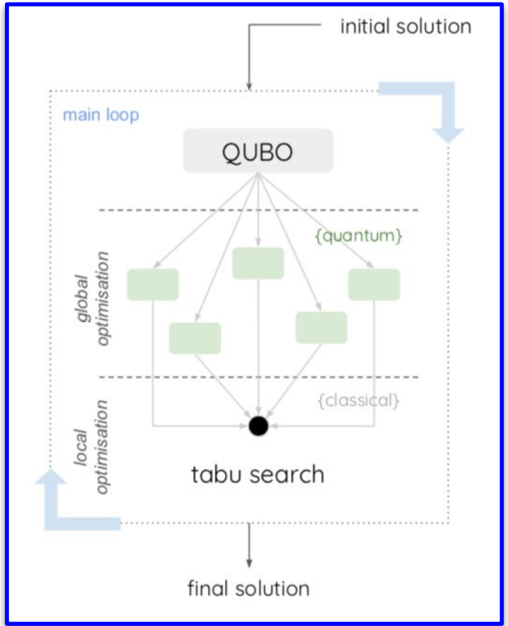
1) Pair hits → **Doublets**
2) Doublets → **Triplets**
3) Triplets → **Quadruplets**
   - Determines Quality of Triplet

Classical Tracking Algorithm



4) Triplet/quadruplets -> **QUBO**
5) **Sub-QUBO/Tabu solve**
   - Qubo Size too large
6) Retrieve Triplet solution sets

Hybrid Classical-Quantum Solver



Lucy Linder 2019

7) **Checked against truth reconstruction
   - Acquire Purity and Recall

Slicing Algorithm: QUBO Design

Lucy Linder
2019

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

Linear Triplet Weighting

Quadruplet Quality Value

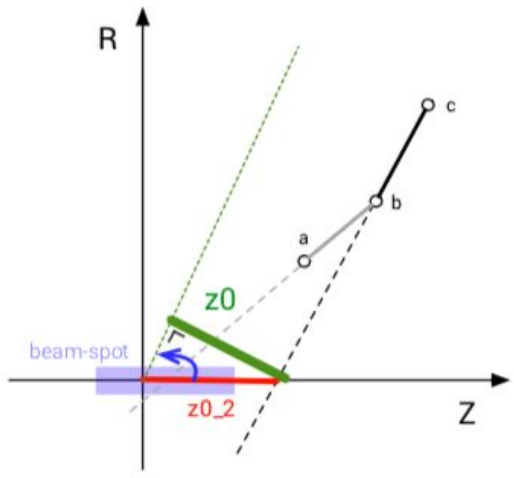
$$b_{ij} = \begin{cases} -S(Ti, Tj), & \text{if } (T_i, T_j) \text{ form a quadruplet,} \\ \zeta & \text{if } (T_i, T_j) \text{ are in conflict,} \\ 0 & \text{otherwise.} \end{cases}$$

Quadruplet quality defined by composing triplet trajectories

- b_{ij} more negative for best triplet match

Linear Weighting terms:

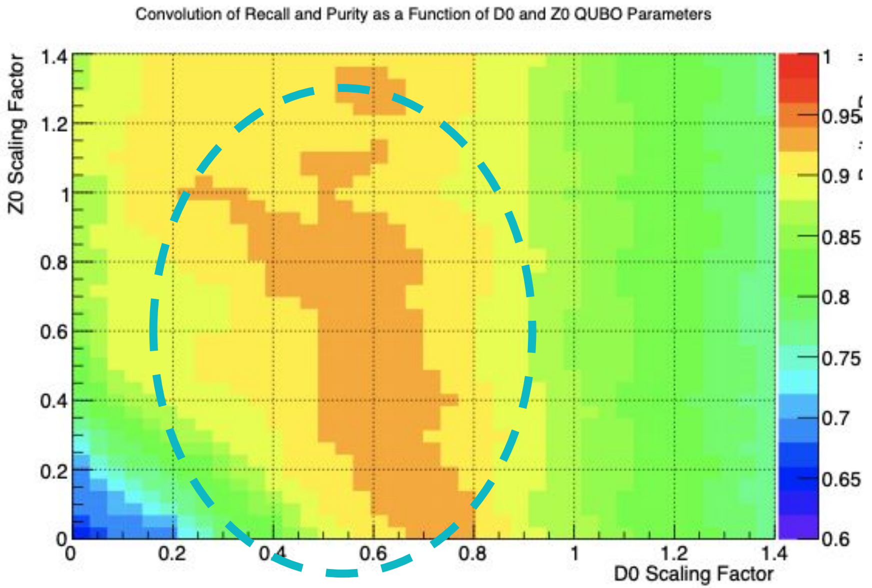
- Not necessary to run algorithm
- Applied to all triplet nodes
- Values triplet trajectory towards origin
- Showed initial success, potentially oversimplified



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

Results: Parameter Optimization

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



Scan QUBO parameter space
- Previous parameters **arbitrary**
- Only affects linear QUBO terms

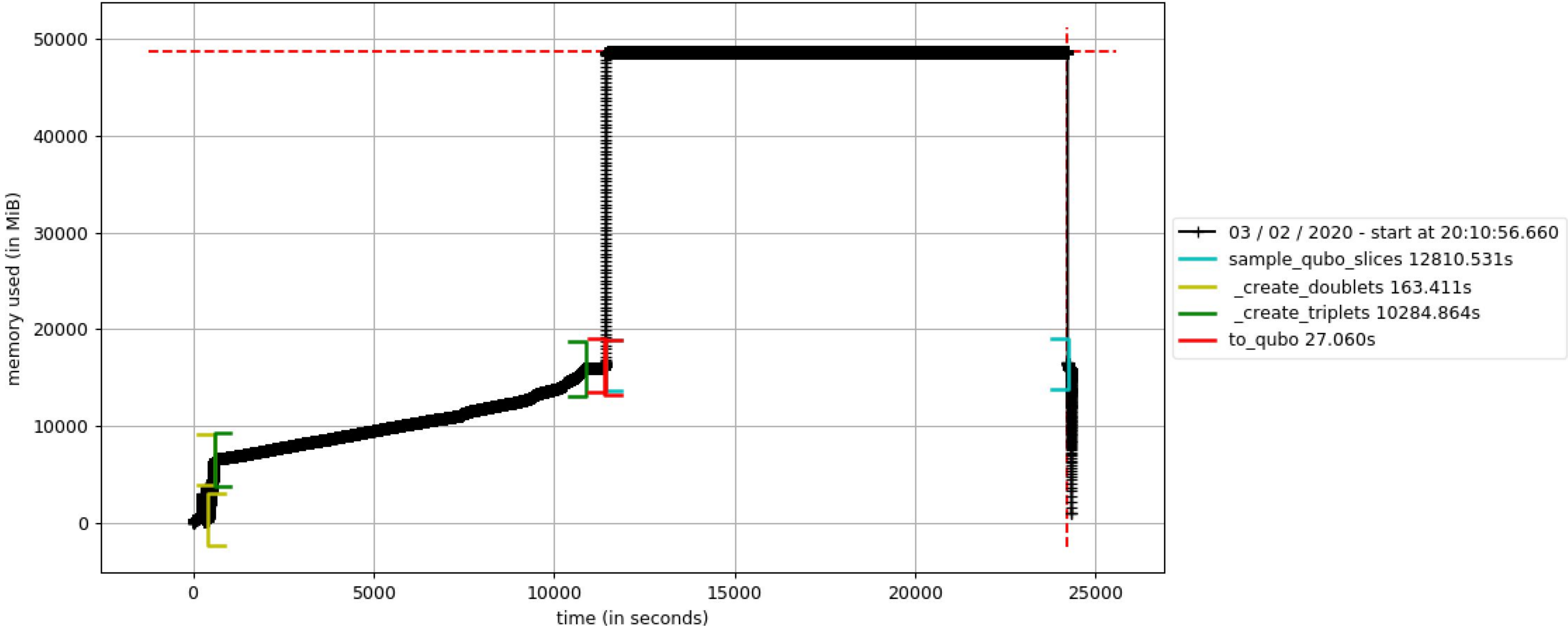
Simulated QBsolv used
- Similar performance results to Quantum

Event Density: 50% of total event

Conclusion: Promising region of penalty parameters

Metrics
- **Purity** (precision): Found Truth Tracks/Total Tracks
- **Recall** (efficiency): Real Tracks/Total Truth Tracks
- Both < 1

Complications….

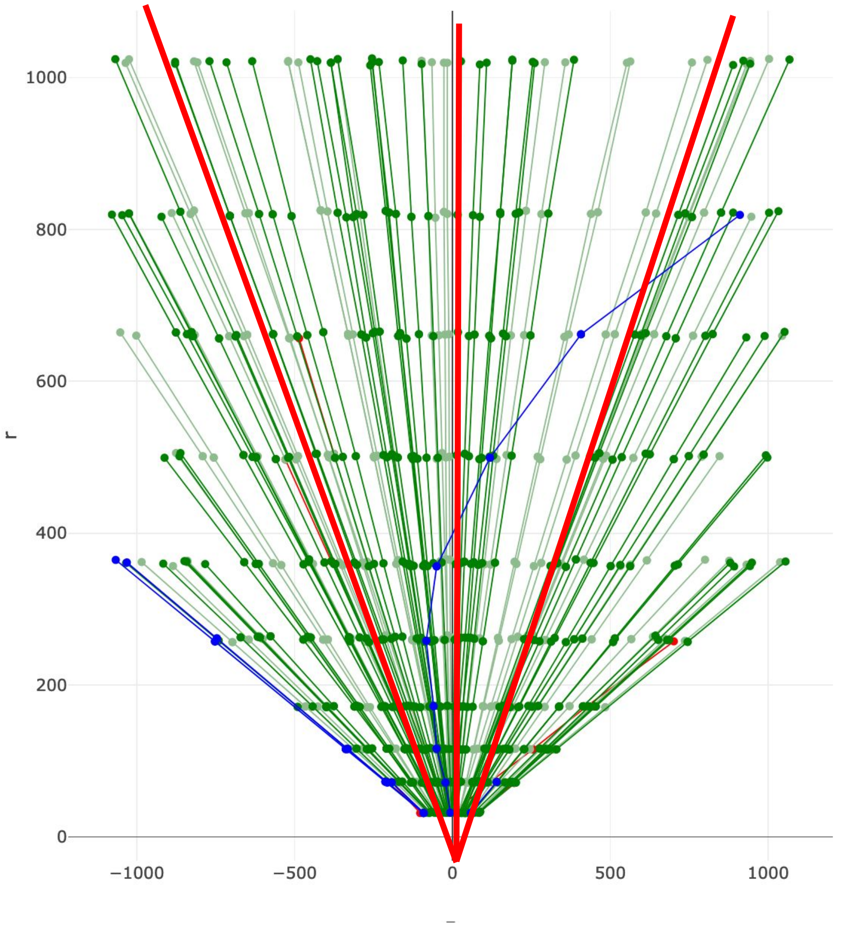


Slicing Algorithm: Summary

1) Pair hits → **Doublets**
2) Doublets → **Triplets**
   - **Requires same r-z plane slice**
3) Triplets → **Quadruplets**
   - Determines Quality of Triplet

4) Triplet/quadruplets -> **QUBO**
5) **Sub-QUBO/Tabu solve**
   - Qubo Size too large
6) Retrieve Triplet solution sets
   - Resolve overlap from sets

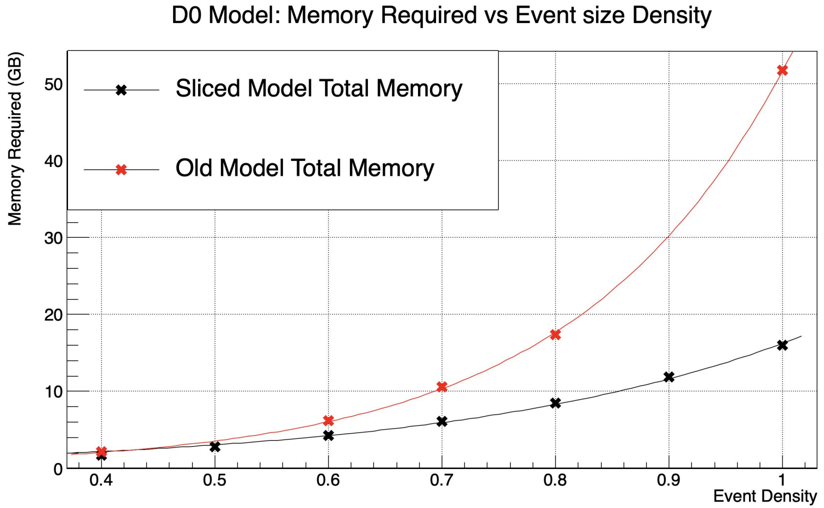
7) **Checked against truth reconstruction
   - Acquire Purity and Recall

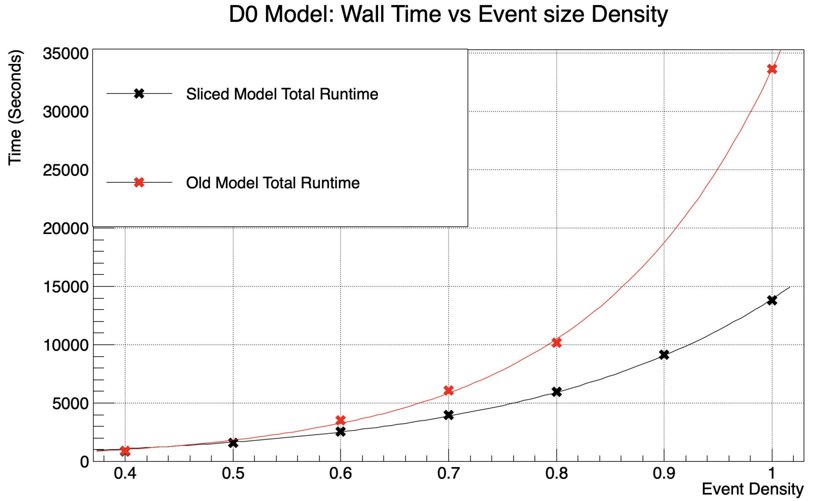


Results: Slicing

- QBsolv memory/ time consumption dominates full density non-sliced events
- Considerable improvement in sliced algorithm runtime

- In this run:
  4 r-z plane angular slices





Results: Slicing

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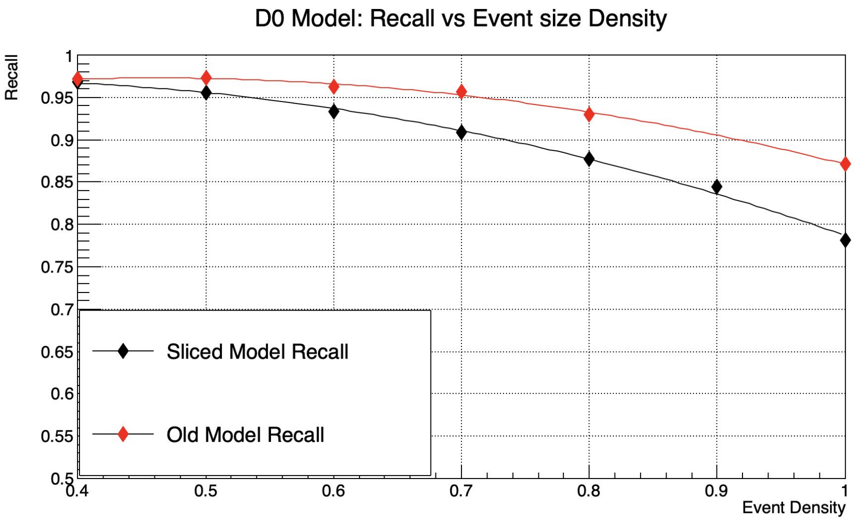
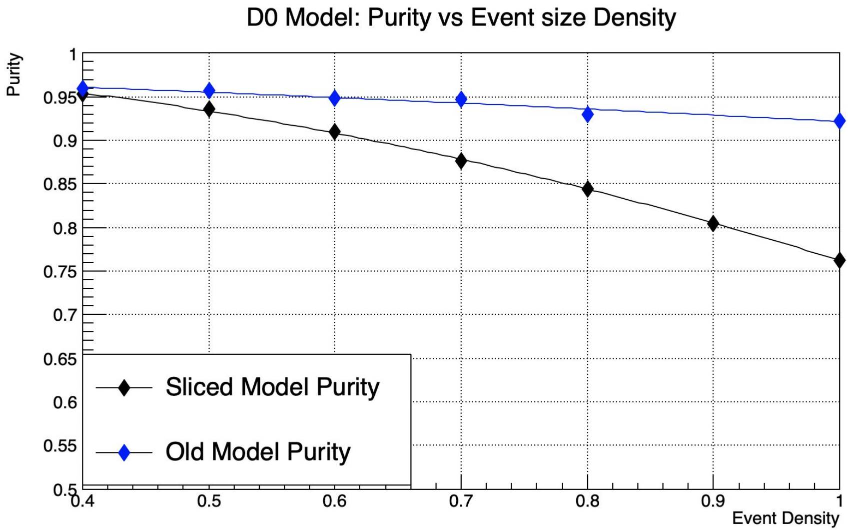
  4 r-z plane angular slices

Considerable Recall and Purity Tradeoff

~ 8% Recall loss
~ 15% Purity loss





Outlook

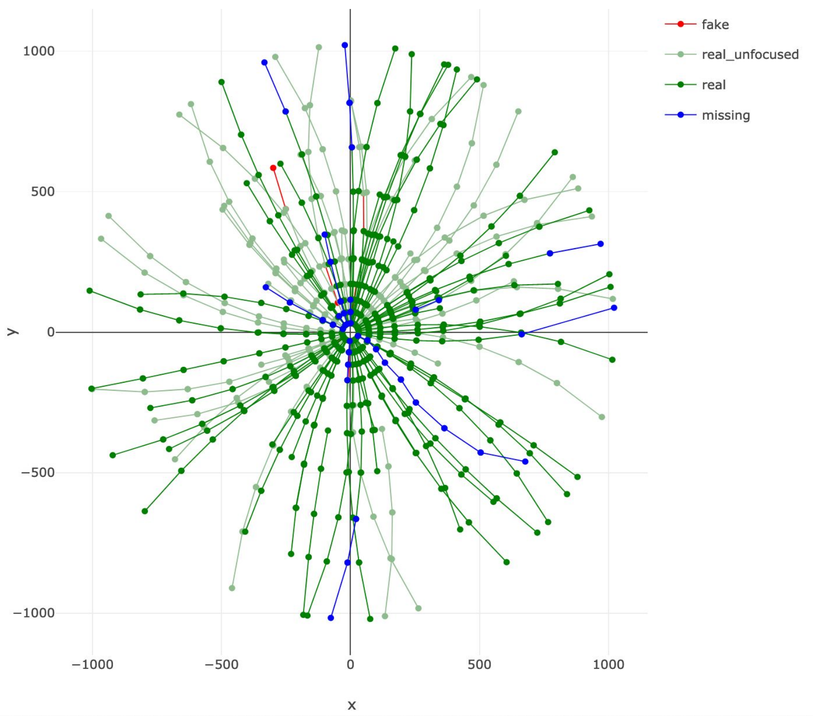
Dataset generation with ACTS

- **Realistic Data**
- Systematic errors of overlap algorithm
-

Determine event density limitation

Potential to work with new D Wave 5000 Qbit Pegasus architecture

- On the cloud sometime in **2020**



Thank you for your attention!

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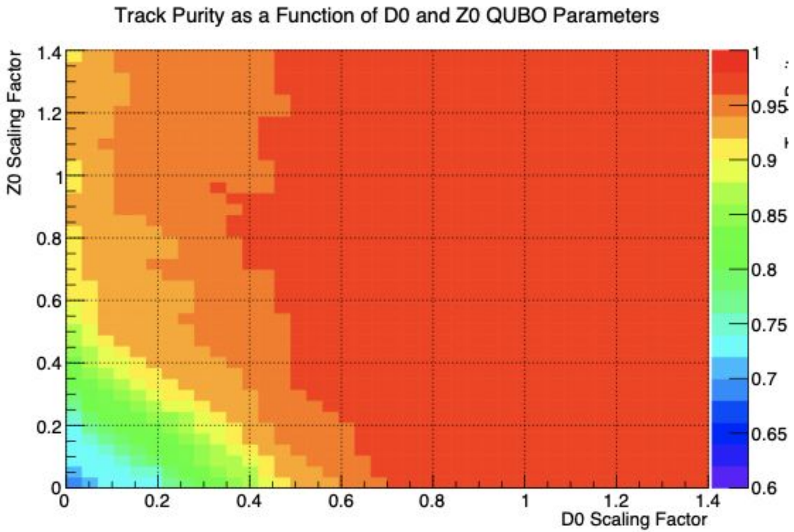
WNPPC
2020

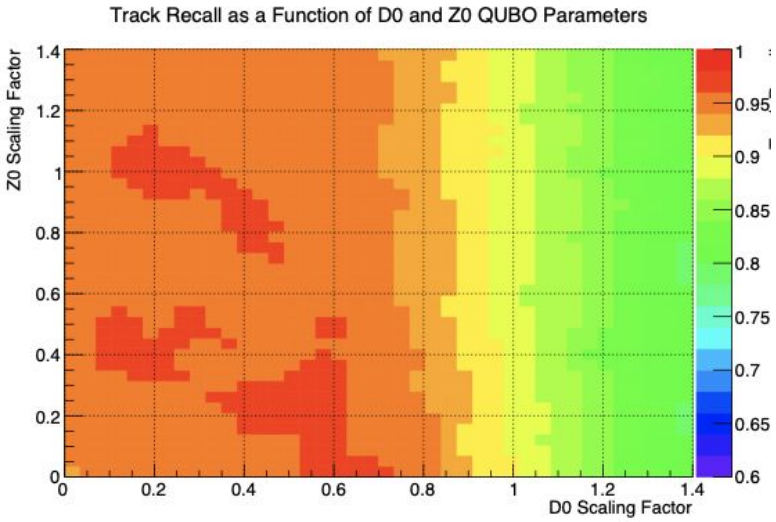
BONUS

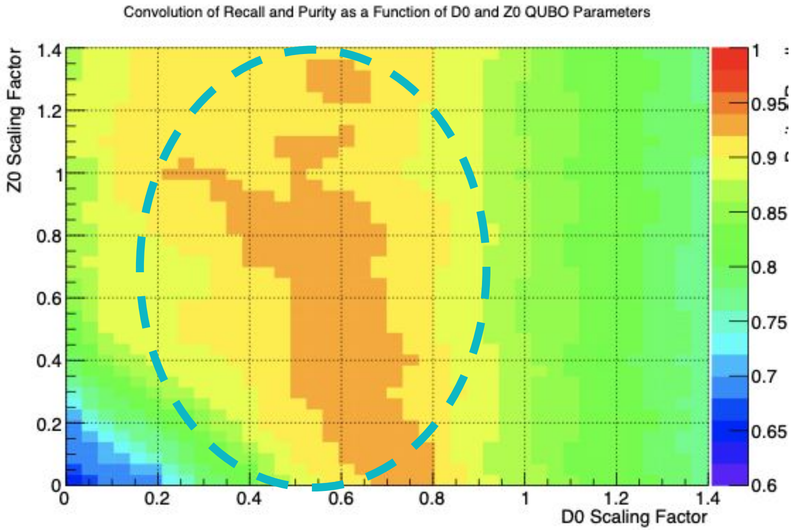
Parameter Optimization: Explicit

- Simulated QBsolv
- Promising region of penalty parameters

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







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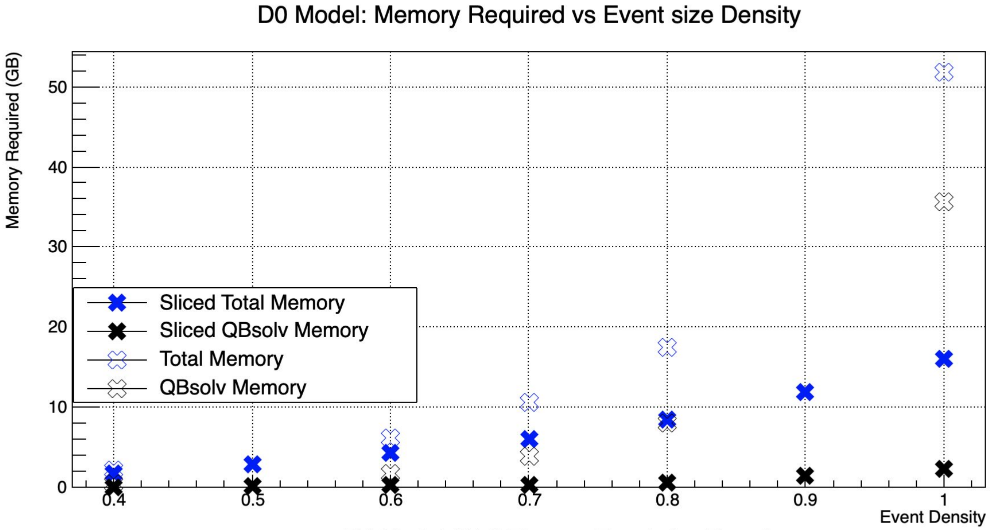
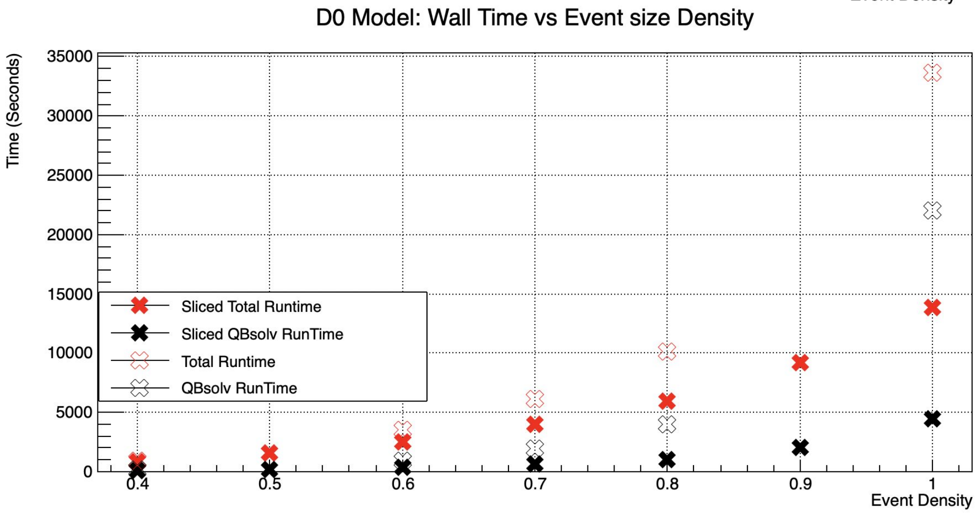
BONUS

Slicing Improvements: Explicit





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BONUS

Slicing Algorithm: Dataset and Detector PUT THIS IN SLIDE WITH TRACKING

TrackML challenge (2019)

Designed to challenge current tracking algorithms

- Similar to ATLAS ITK Detector

Competition complete, excellent toy dataset

- Complete with Benchmarks!

Parameters:

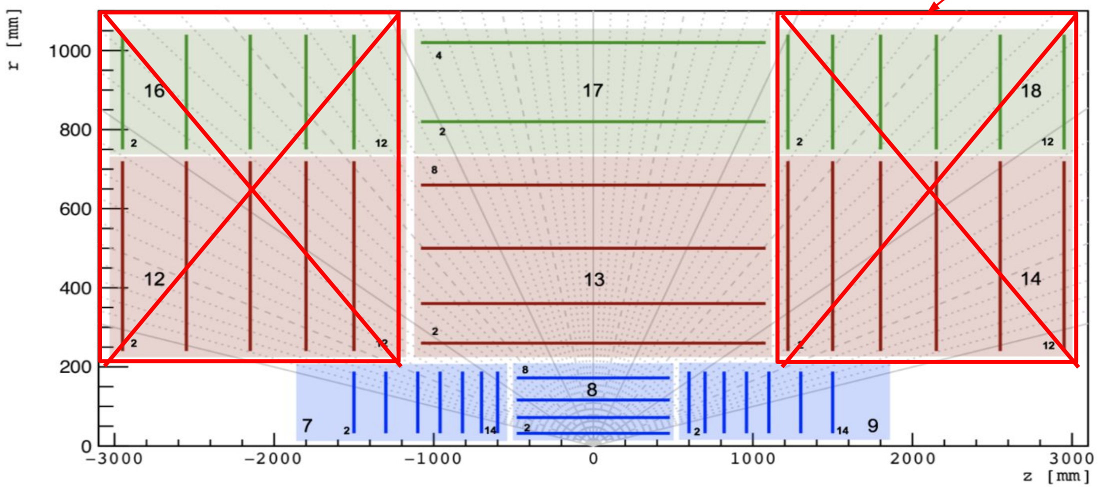
- ~11,000 Particles/event
- ~110,000 Hits/event
- (INSERT # HERE) Slices w.r.t ϕ and η

Simplifications:

- End-caps removed
- No Calorimeter data
- Truth tracks > 4 hits

End-Caps removed

Kaggle TrackML Detector Topology: R-Z plane



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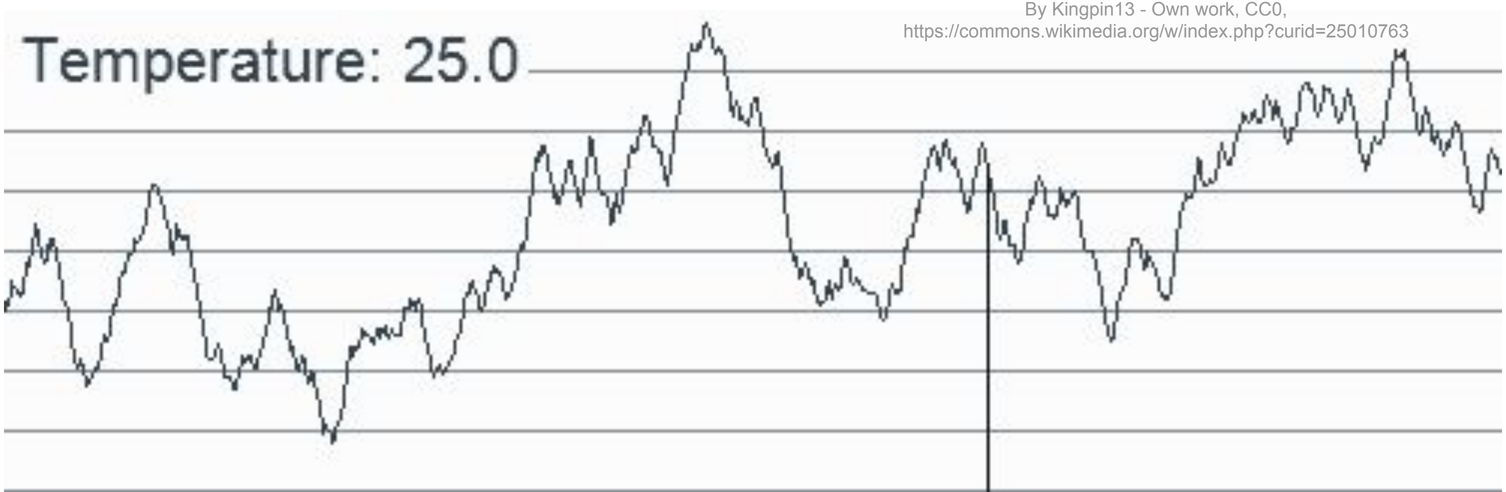
Annealing: Classical

Classical Annealing:
- [Heuristic] algorithm
- Probe local function region
- Look for improvements in solutions
- Probability function avoids local minima
- NP-Hard problem class

Classical Annealing: **Cooling Down**

By Kingpin13 - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=25010763



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