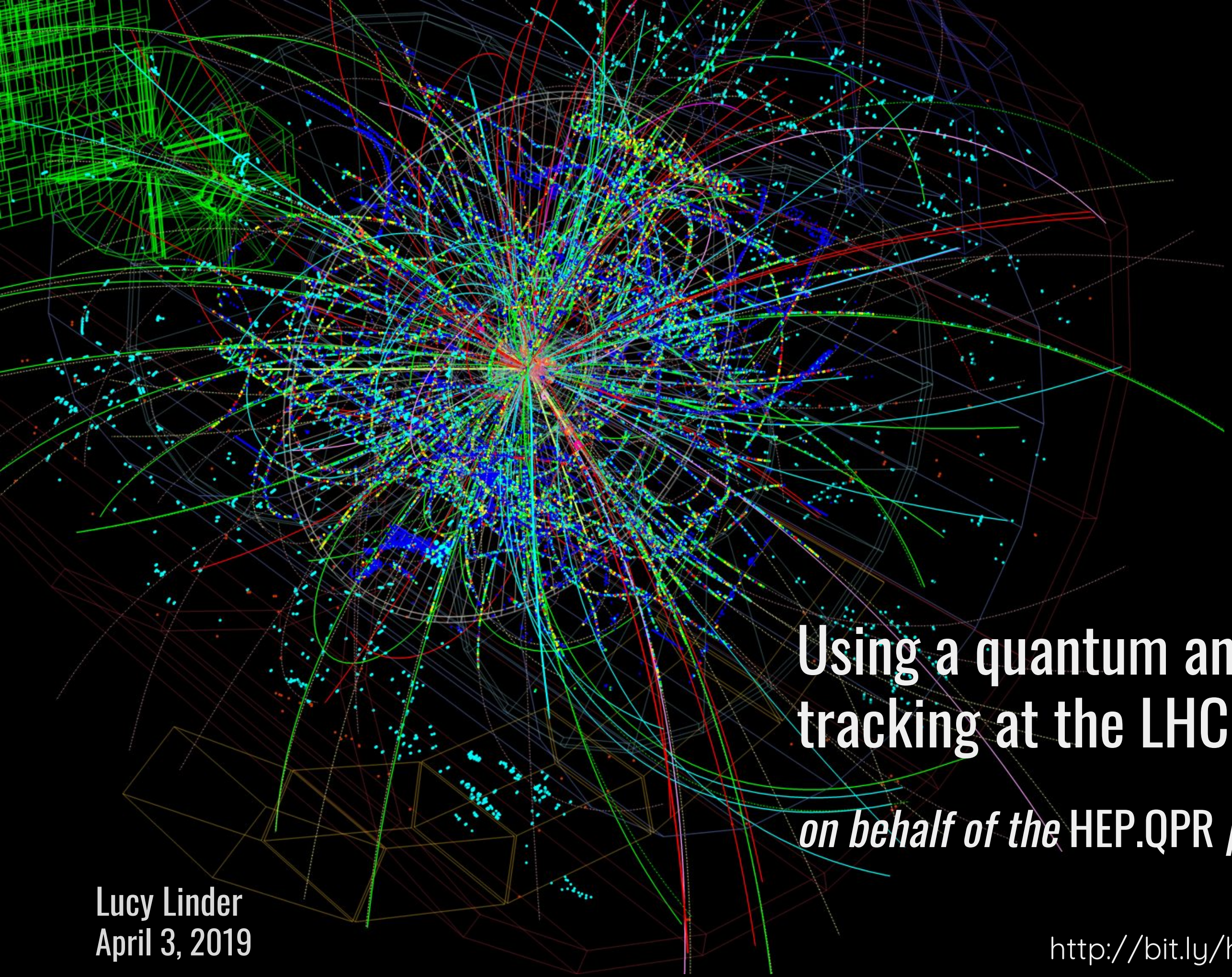


BERKELEY LAB
U.S. DEPARTMENT OF ENERGY
Office of Science
iCoSys
Institute of Complex Systems
(HEIA-FR)

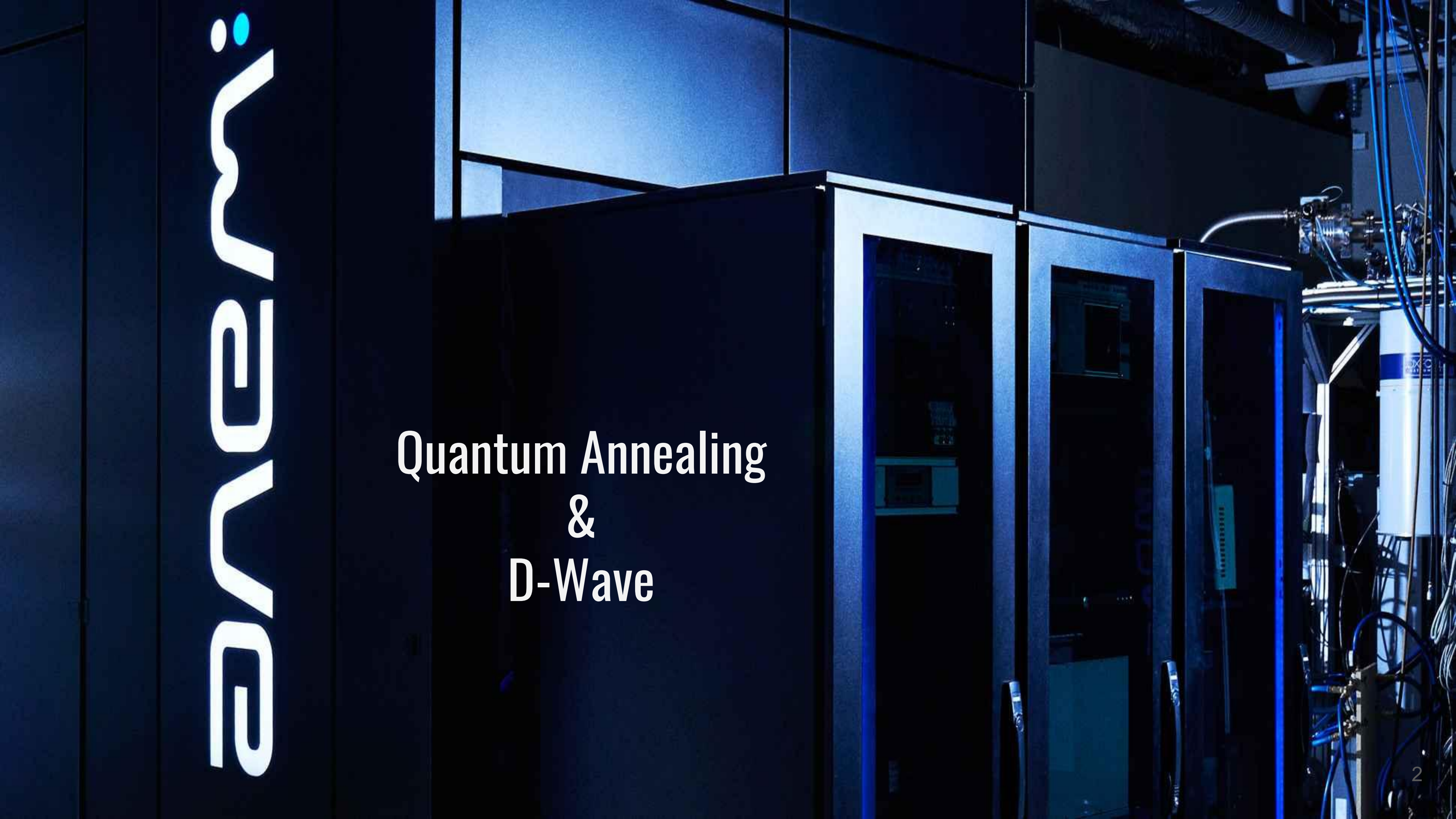
Using a quantum annealer for particle tracking at the LHC

on behalf of the HEP.QPR *project at* LBL

Lucy Linder
April 3, 2019

http://bit.ly/hepqpr-cdots

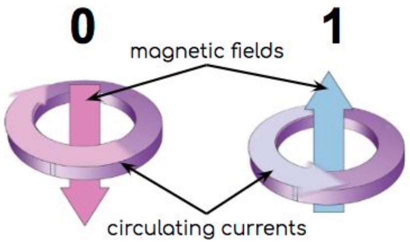
Hes·so
Haute Ecole Spécialisée
de Suisse occidentale
Fachhochschule Westschweiz
University of Applied Sciences and Arts
Western Switzerland



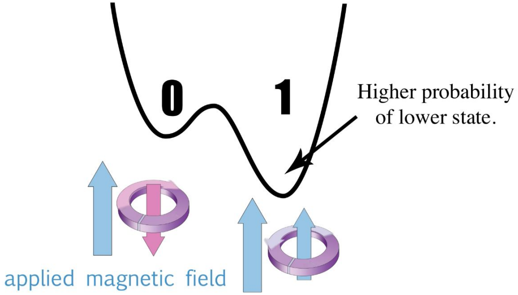
Quantum Annealing
&
D-Wave

QA in D-Wave computers

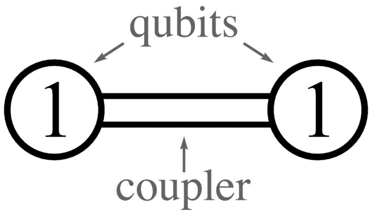
source: dwavesys on YouTube



qubits ⇒ q_i



bias weights ⇒ a_i



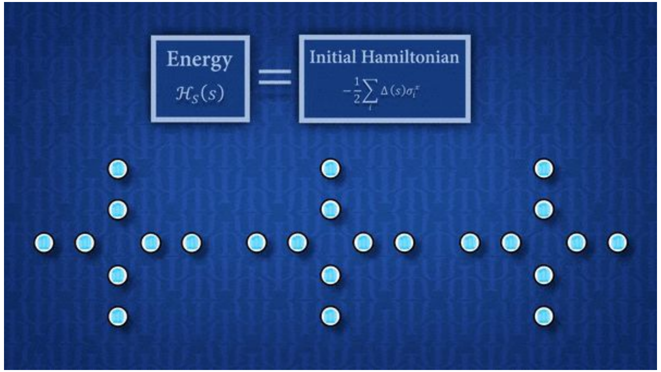
coupling strength ⇒ b_{ij}

quantum machine instruction (QMI)
objective function:

$$O(a;b;q) = \sum_{i=1}^{N} a_i q_i + \sum_{i}^{N}\sum_{j}^{N} b_{ij} q_i q_j \quad q_i \in \{0,1\}$$

QUBO

Quadratic Unconstrained Binary Optimisation



anneal time ~20µs

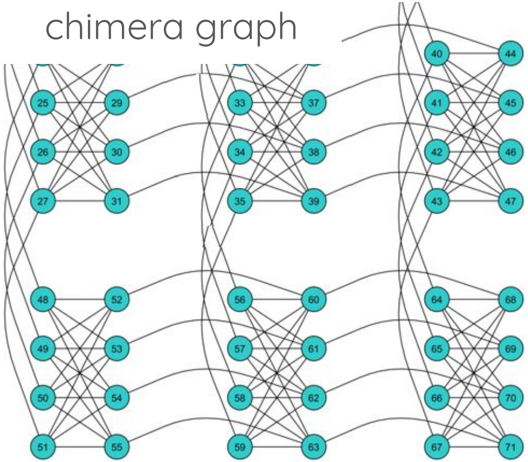
D-Wave hardware & usage

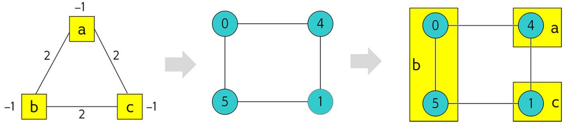
D-Wave 2X (2015)

1152 qubits
3360 couplers

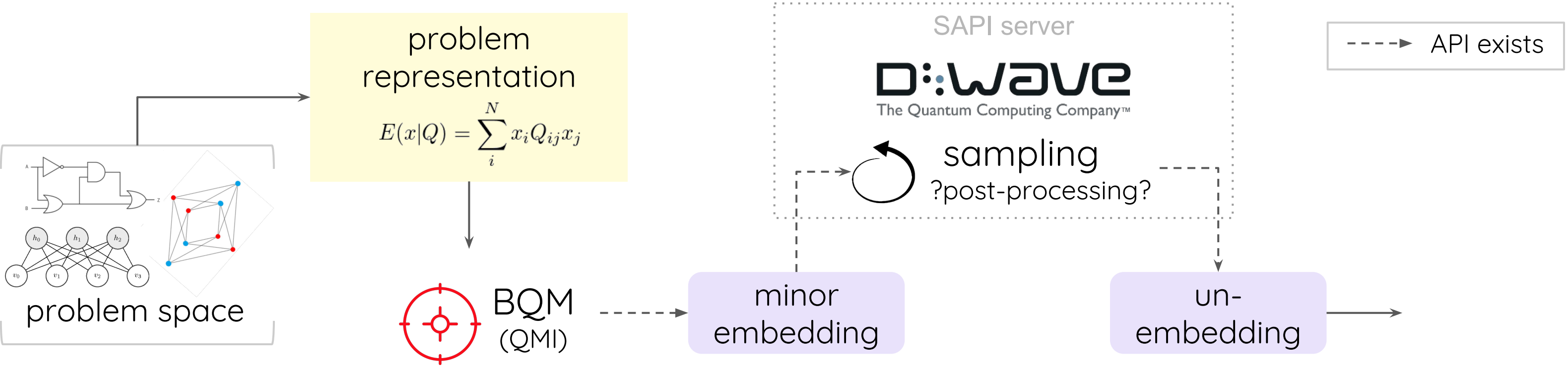
D-Wave 2000Q (2017)

2048 qubits
6016 couplers





minor embedding



QUBO for track reconstruction

Stimpfl-Abele & Garrido (1990) *ref*

“We can regard a *track* with n hits as a set of n-1 consecutive lines [doublets] with a smooth shape and without bifurcation”.

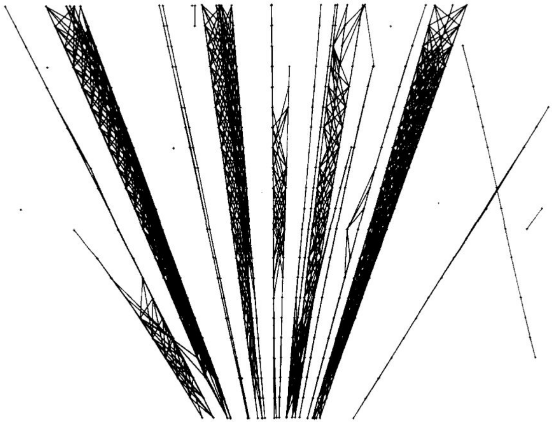


Fig. 2. Display of all generated lines for a real $Z^0 \to$ hadrons (RZ projection).

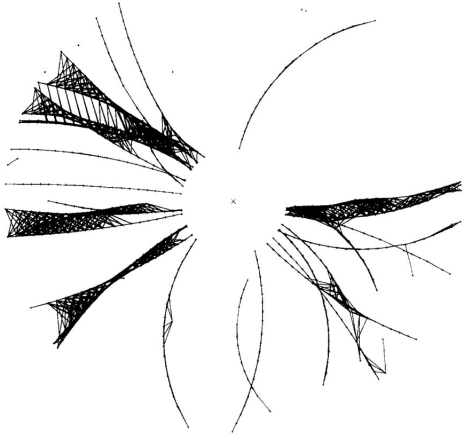


Fig. 1. Display of all generated lines for a real $Z^0 \to$ hadrons (XY projection).

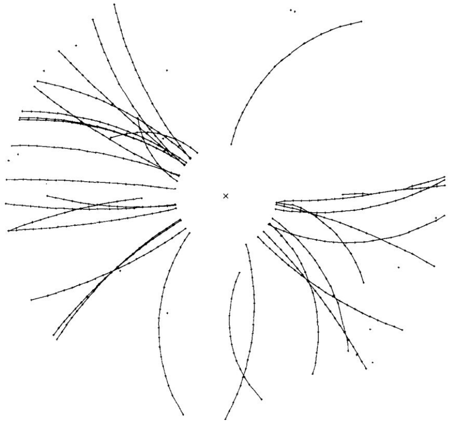


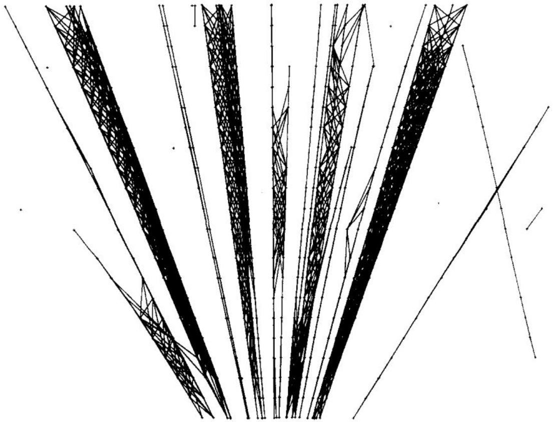
Fig. 3. Display of the activated lines after convergence for a real $Z^0 \to$ hadrons (XY projection).

source: fast track finding with neural nets

1. generate the set of potential doublets (apply early cuts)
2. *binary classification task* to determine which doublets should be kept in the track candidates, using Hopfield Networks

Stimpfl-Abele & Garrido (1990) *ref*

“We can regard a *track* with **n** hits as a set of **n-1** consecutive lines [doublets] with a smooth shape and without bifurcation”.



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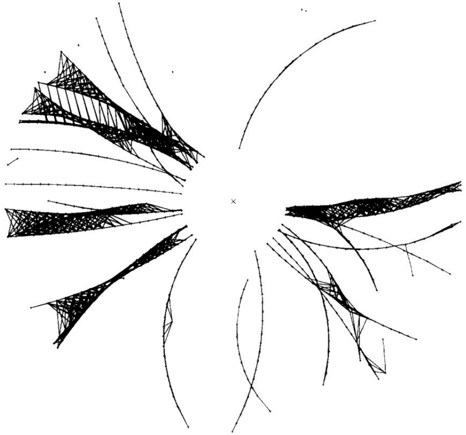

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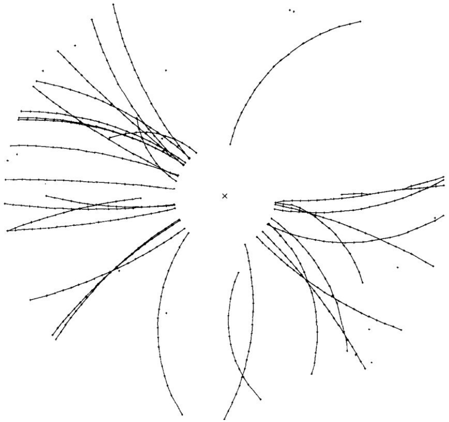


Fig. 3. Display of the activated lines after convergence for a real $Z^0 \to$ hadrons (XY projection).

source: fast track finding with neural nets

1. (generate the set of potential doublets (apply early cuts))

   → use a Python adaptation of the ATLAS online seeding GPU code

2. *binary classification task* to determine which doublets should be kept in the track candidates, using ~~Hopfield Networks~~ Quantum Annealing

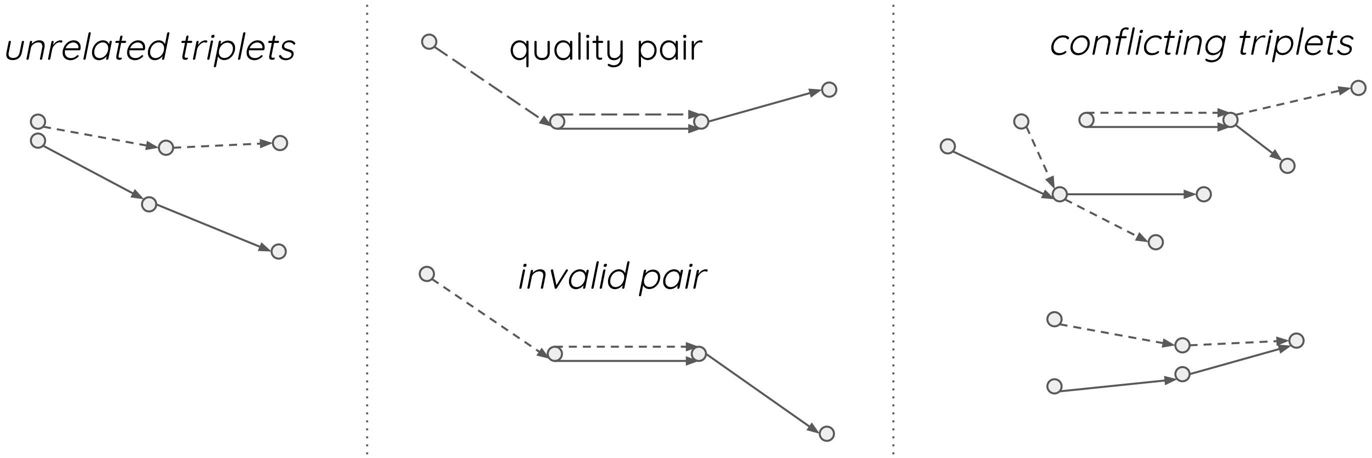
~~doublets~~ triplets !

Internally, focus on triplets of hits: $T_{a,b,c}$

Triplets can form interesting pairs or be in conflict.

binary classification of ***triplets***

→ any P_t
→ any vertex location



The energy function

Stimpfl-Abele

$$E = -\frac{1}{2}\Big[\sum_{kln} T_{kln} V_{kl} V_{ln} - \alpha\Big(\sum_{klm(l\neq m)} V_{kl} V_{km} + \sum_{klm(k\neq m)} V_{kl} V_{ml}\Big) - \beta\Big(\sum_{mn} V_{mn} - N_a\Big)\Big], \quad V \in \{0,1\}$$

Select the best triplets, in the form of pairs, that will constitute the track candidates:

$$E = \alpha\Big(\sum_{i}^{N} T_i\Big) - \Big(\sum_{i,j(\in pairs)} S_{ij} T_i T_j\Big) + \zeta\Big(\sum_{i,k(\in conflicts)} T_i T_k\Big) \quad T \in \{0,1\}$$

"***bias weight***" triplet prior
can be set to 0

"***connection strength***",
interest of [keeping]
a pair of triplets

avoid "***conflicts***", a hit belongs
to at most one track

The energy function: QUBO

$$E = \alpha\Big(\sum_{i}^{N} T_i\Big) - \Big(\sum_{i,j(\in qplets)} S_{ij} T_i T_j\Big) + \zeta\Big(\sum_{i,k(\in conflicts)} T_i T_k\Big) \quad T \in \{0,1\}$$

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

$$b_{i,j} = \begin{cases} -S_{ij}, & \text{if } (Ti, Tj) \text{ form a pair that chould form a track,} \\ \zeta & \text{if } (Ti, Tj) \text{ are in conflict,} \\ 0 & \text{otherwise.} \end{cases}$$

Underlying math

a track of n hits is a set of n-2 triplets that can be combined into n-3 pairs

a set of track candidates is a set of triplets with no conflict

A triplet $\mathrm{T}_{a,b,c}$ has a higher quality when:

- it has little to no hole: $\mathbf{H = 0}$
- the menger curvature $\mathbf{curv(a,b,c)}$ formed by the three hits in the X-Y plane is small;
- doublets ab and bc have similar θ angles: $\mathbf{drz(T_{a,b,c}) = |\varsigma(\theta_{ab}, \theta_{bc})|}$ is small

A pair $(\mathrm{T}_i, \mathrm{T}_j)$ has a higher quality when:

- it has few holes: $\mathbf{H_{ij} = 0}$
- there are similar curvatures::
  $\mathbf{dcurv_{ij} = |\varsigma(curv(T_i), curv(T_j))|}$ is small
- hits are aligned in R-Z:
  $\mathbf{drz_{ij} = max(drz(T_i), drz(T_j))}$ is small

The interest of connecting two triplets into a pair can be expressed as:

$$S_{ij} = \frac{\alpha\left(\beta(1-dcurv_{ij})^{\gamma} + (1-\beta)(1-drz_{ij})^{\delta}\right)}{(1+H_{ij})^{\epsilon}}$$

β=0.5,
ε=2,
others=1

$$S_{ij} = \frac{1-\frac{1}{2}(dcurv_{ij}+drz_{ij})}{(1+H_{ij})^{2}}$$

Experimental setup

Dataset

TrackML dataset (== HL-LHC) with events split into lower multiplicity datasets:.

- select P% of particles
- select P% of noise

Set weight=0 for hits belonging to particles with:

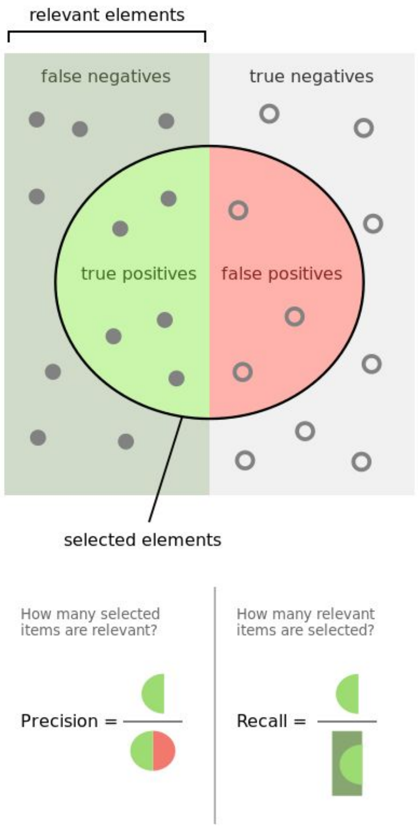
- $P_T < 1$ GeV or
- less than 5 hits

endcaps
double hits

tune the model for that !

Metrics

- TrackML score
- precision (~purity)
- recall (~efficiency)



false negative = missings
false positive = fakes

Machines

- CORI (1 Haswell node)
- D-Wave 2000Q (leap)
- D-Wave 2X (LANL)

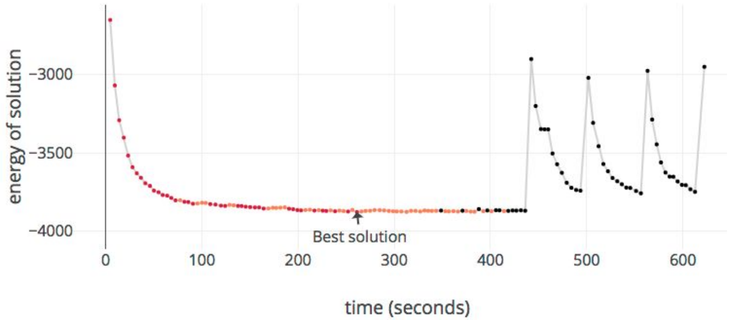
QUBO solver

iterative hybrid classical/quantum algorithm

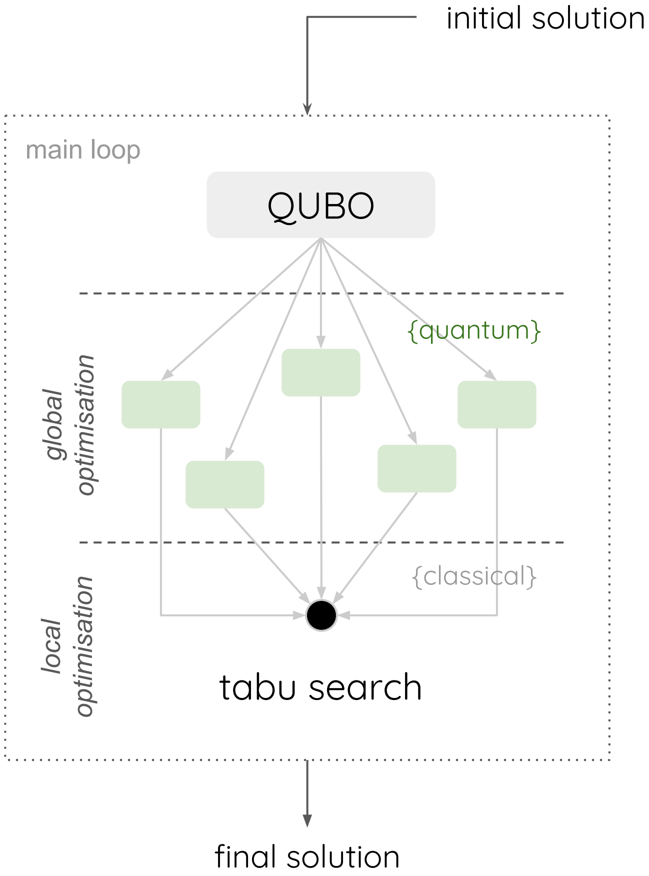
QBSOLV

large and/or densely connected QUBOs split into sub-QUBOs fitting the D-Wave hardware.

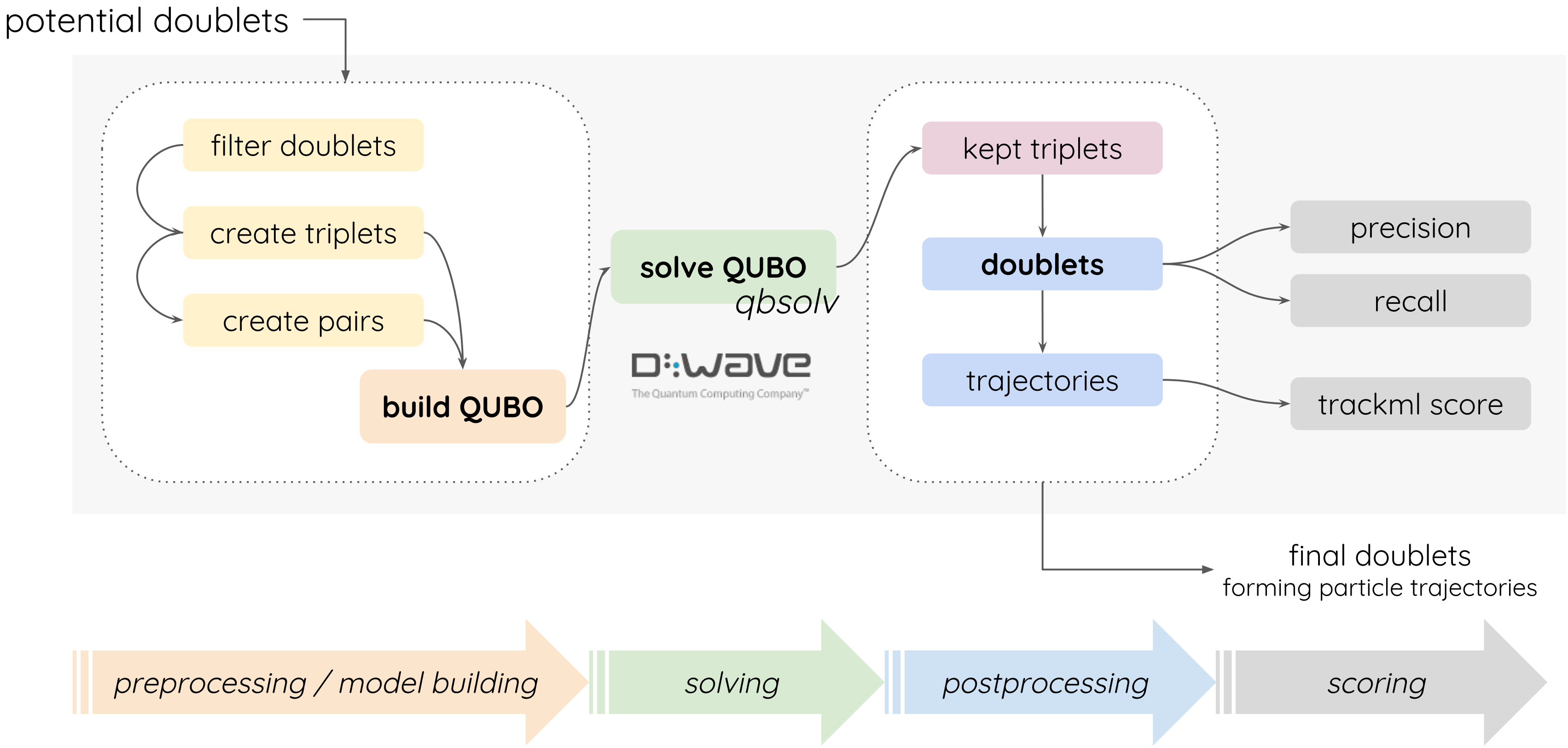
Tabu search on the recomposed solutions.



evolution of the solution in each [qbsolv] loop.
The solution is sometimes randomised to escape local minima.



Algorithm overview



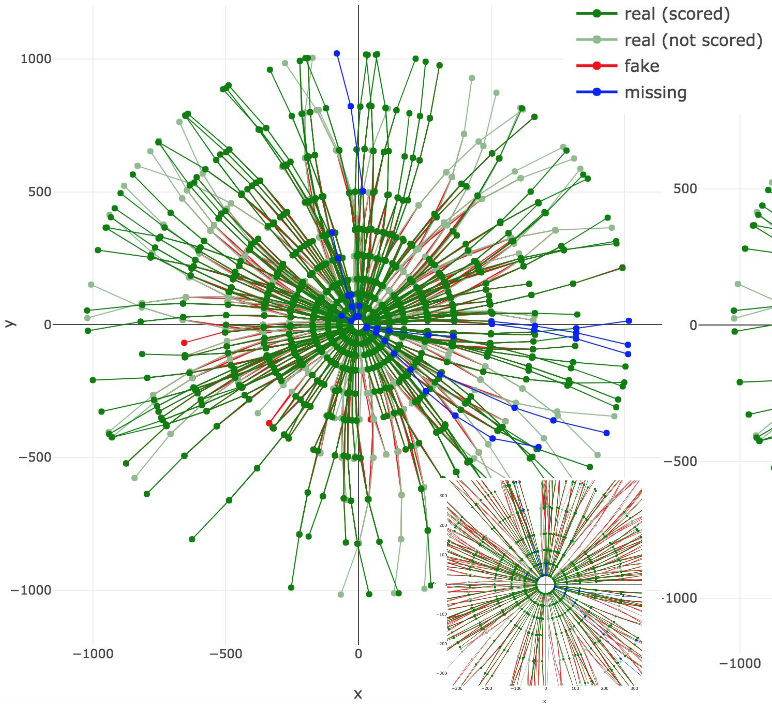
Results

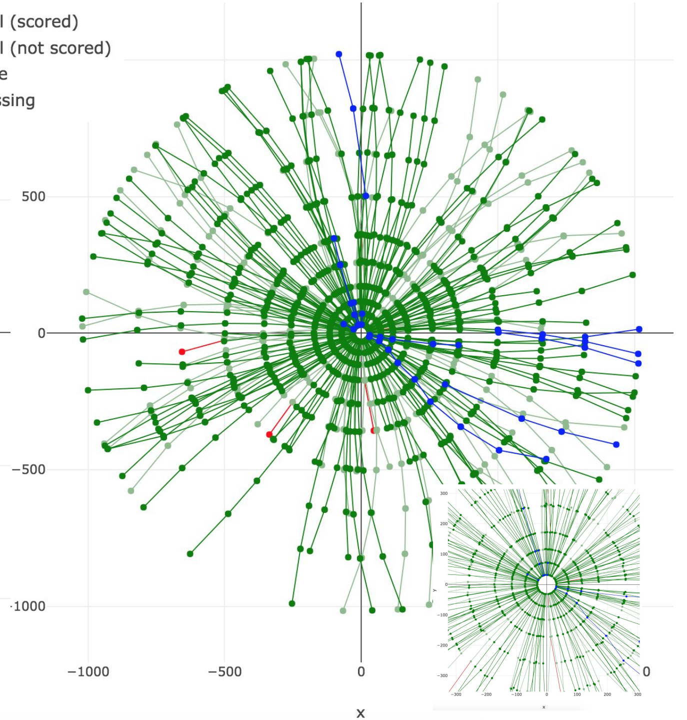
Results

dataset size: ~20%

1,637 particles, 11,030 hits

plotting error: too many doublets 392529





392,529 doublets
p=**0.26**%, r=**99.15**%

57.3s
build QUBO

2,546 doublets
(2,964 triplets)
QUBO size: 14,345

17.1s
sample QUBO
running on CPU

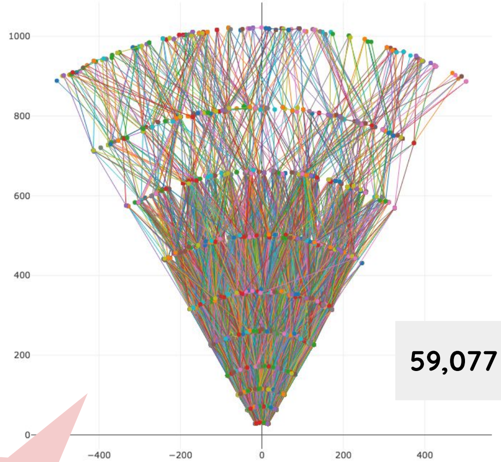
1,512 doublets
p=**99.13**%, r=**97.06**%

trackml score **97.55**%

Performances at low Pt

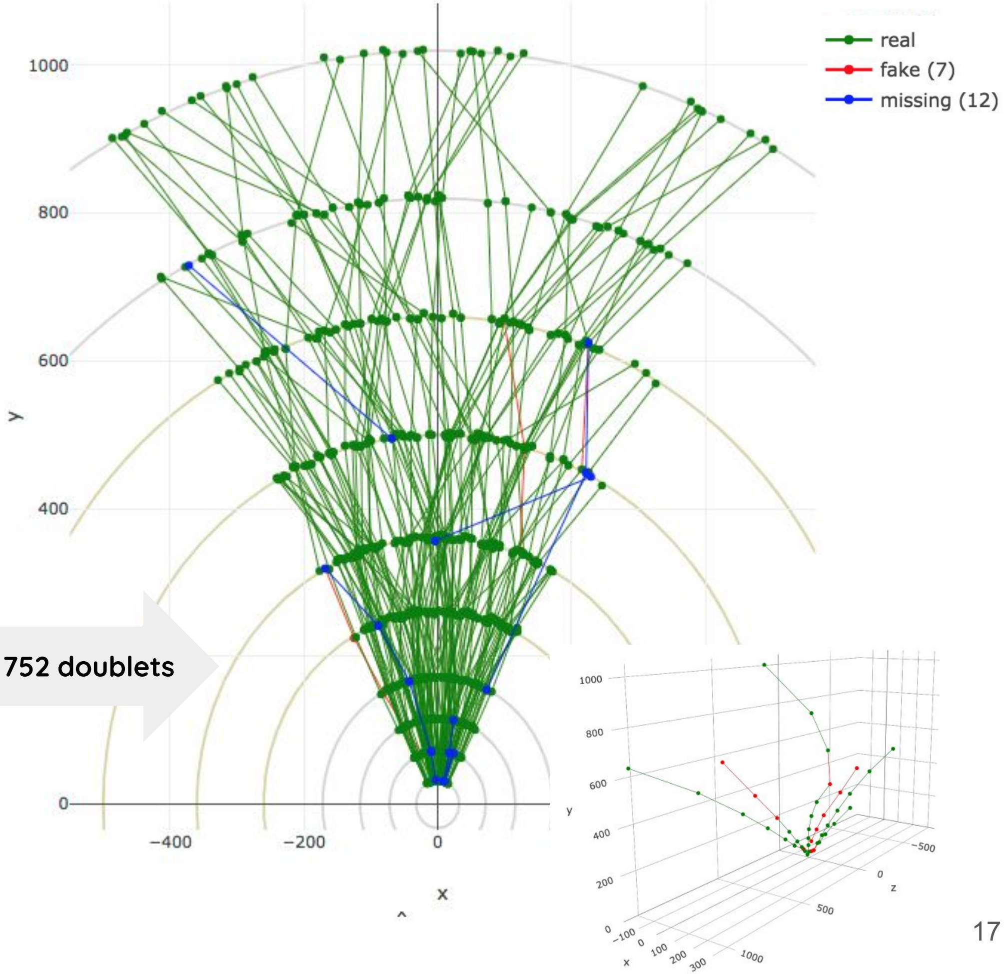
186 particles in a phi slice of π/3

precision (%): 98.5, recall (%): 98.4,
trackml score (%): **98.35**



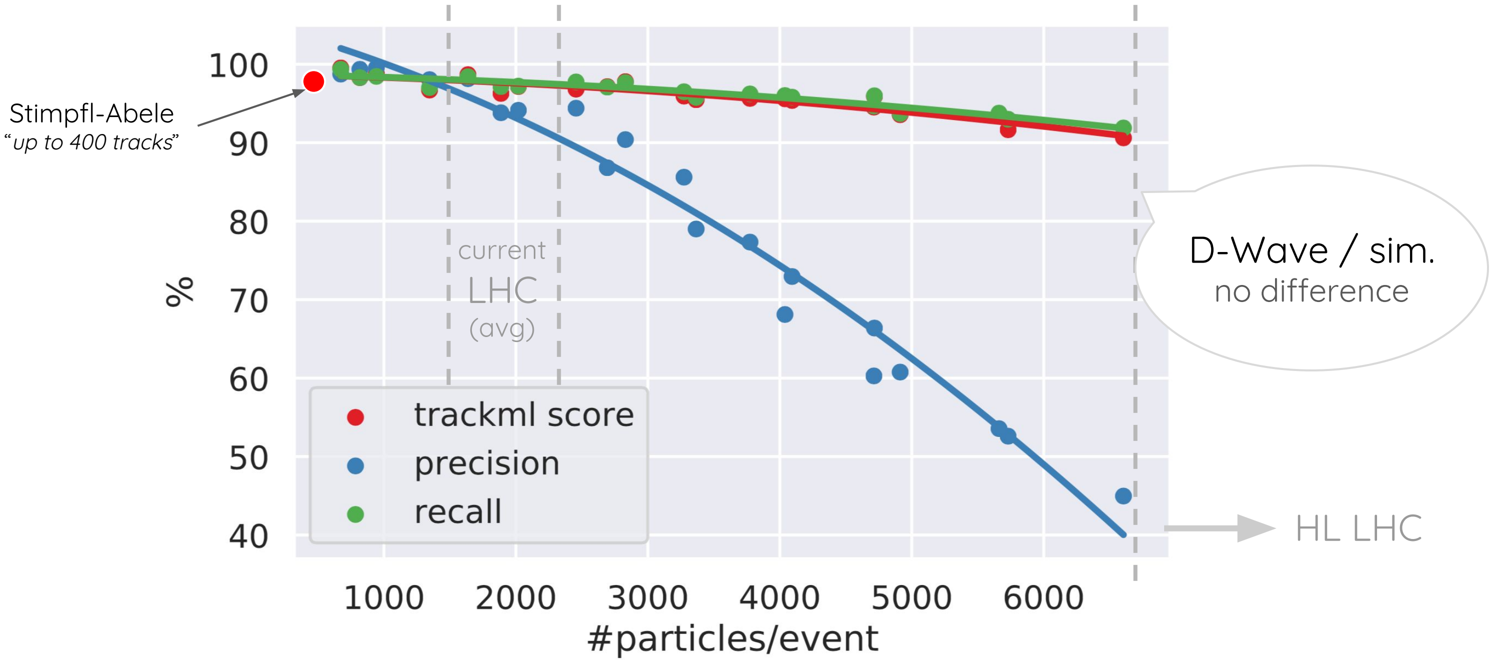
QUBO size
68,043

59,077 ⇒ 752 doublets



Physics performance

Full TrackML event 6,900 - 14,000 particles, Pt ≥ 150 MeV, ~15% noise/lower Pt hits
recall: no endcaps & no double hits, focus on $p_t \geq 1$ GeV BUT no hypothesis on vertex location



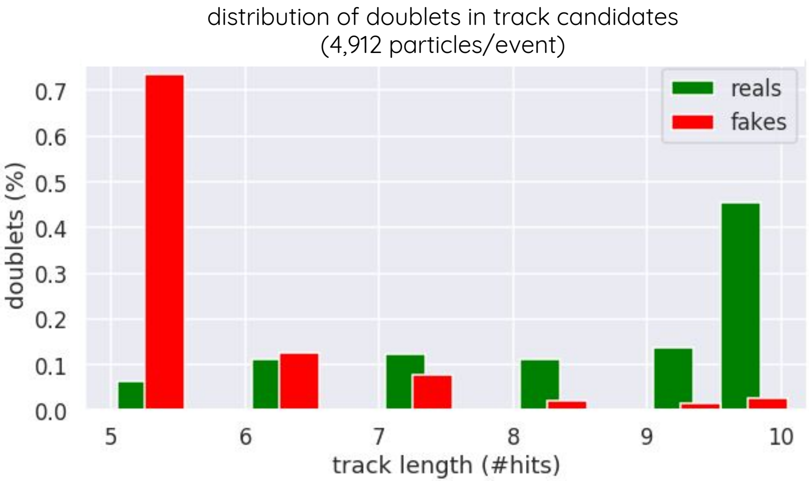
> 90% recall (efficiency) and **trackml** score on doublets classification

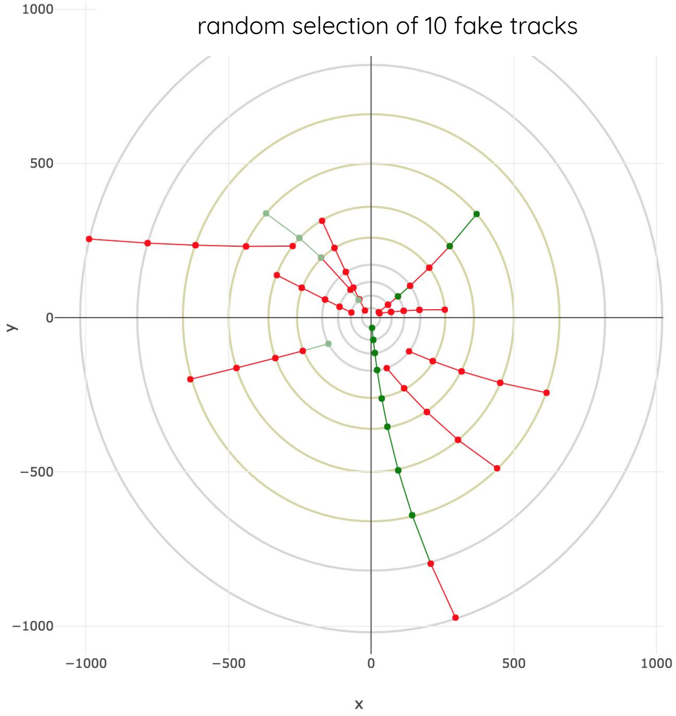
What about the fakes ?

"The biggest difference [with conventional methods] is the number of wrongly associated coordinates [...]

soft constraints and very simple geometrical constants is not as good as a sophisticated algorithm based on hard constraints (fits)".

Stimpfl-Abele & Garrido, [fast track finding with neural networks]()



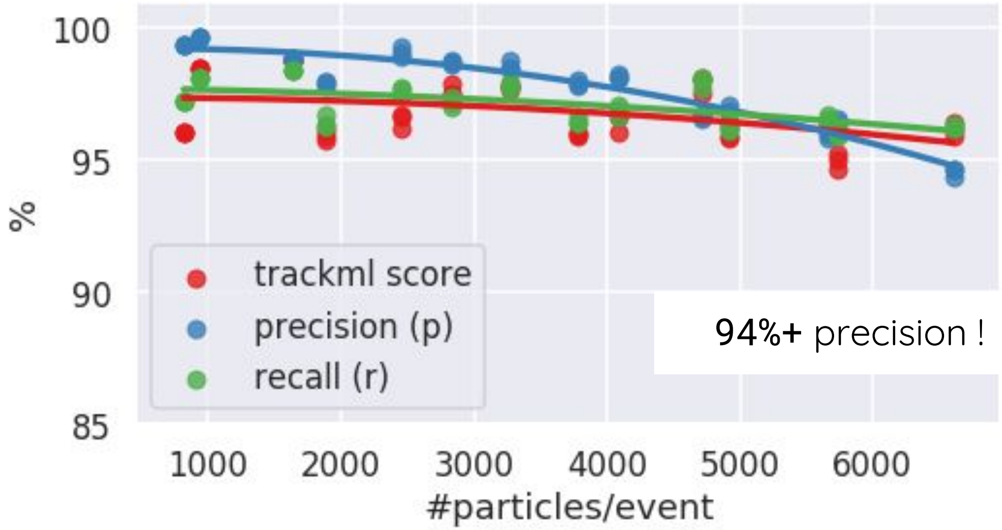


→ post-processing *should* let us filter many fakes

Improvement (TrackML-only)

~~fixed~~ *variable* bias weights

penalty based on the triplet's impact parameters (D0, Z0)



⚠ introduces biases and reintroduces a hypothesis on the vertex location

Future work

improvements
& tuning

- ⇢ hyperparameter + code optimization
- ⇢ reduce fake tracks post-processing, other models, ...
- ⇢ include more properties e.g. magnetic field,

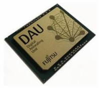
benchmarks & speedup

D-Wave
Fujitsu digital annealer
other QUBO solvers

- ⇢ study physics performance
- ⇢ study timing performance

tests

- bigger datasets ⇠
- noise level ⇠
- qbsolv alternatives ⇠



Resources

HEP.QPR website
https://hep-qpr.lbl.gov

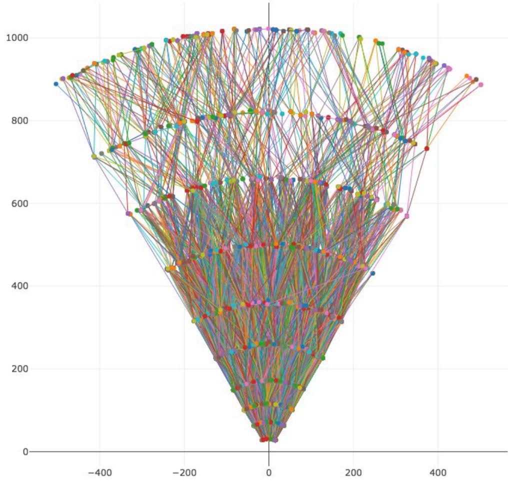
publication preprint
https://arxiv.org/abs/1902.08324

Github repository (and results)
https://github.com/derlin/hepqpr-qallse

Master Thesis report
https://github.com/derlin/hepqpr-qallse/tree/master/doc

» **arXiv:1902.08324** «

Thank you for your attention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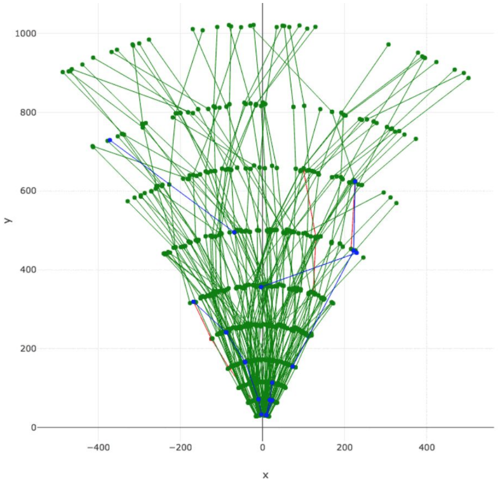
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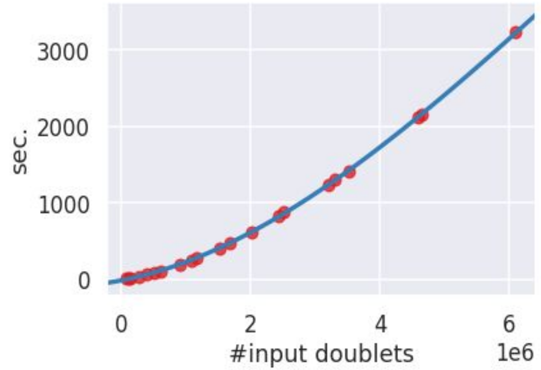
I NOW HAVE ADDITIONAL QUESTIONS

BACKUP

Timing performance

Model building



currently no optimization or parallelization

QUBO solving

neal (dwavesys)

6’600 particles/event = **12 s.**

260,744 QUBO parameters

D-Wave internet latency, shared QPU, qbsolv ….

too early to say !

In the meantime, classical counterparts are surprisingly efficient.

Basics of QA

adiabatic theorem of quantum mechanics,

a physical system remains in the ground state if $\left\{ \begin{array}{l} \text{perturbations are slow} \\ \text{there is a gap} \end{array} \right\}$

QA recipe:

initial Hamiltonian H_0

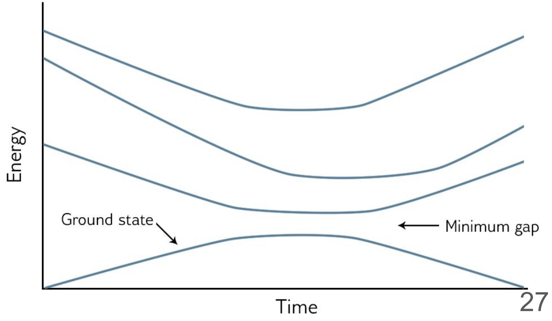
problem Hamiltonian H_p

$\mathtt{H(s)=A(s)H_o+B(s)H_p}$ with

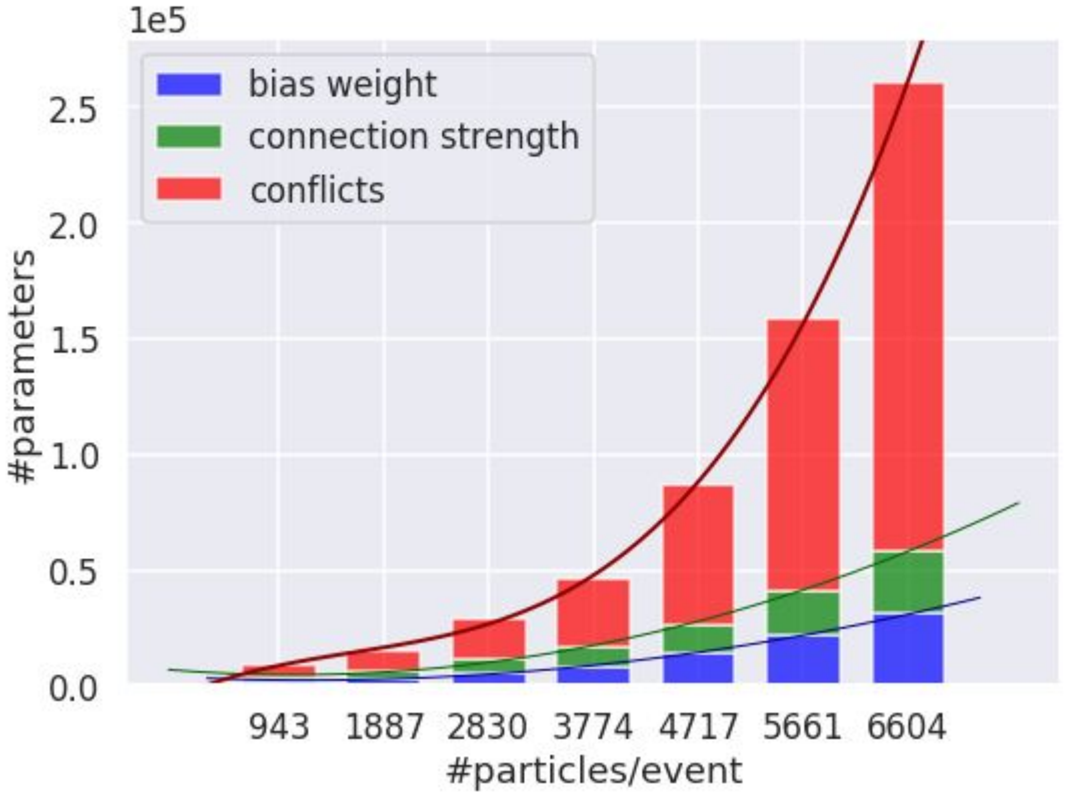
$\mathtt{A(s)}\searrow$ and $\mathtt{B(s)}\nearrow$ given $\mathtt{s = t/t_f} \leqslant 1$ (t_f = *anneal time*)

If the adiabatic conditions are respected,

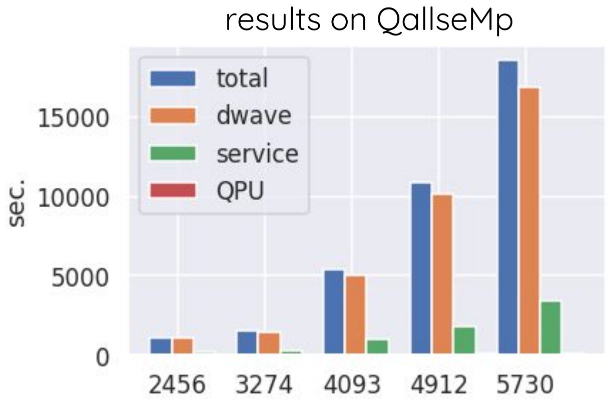
the system's ground state at $\mathtt{t=t_f}$ encodes the solution.



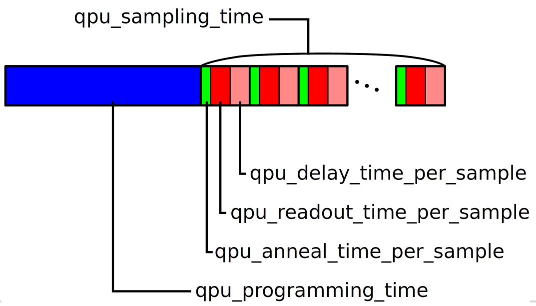
QUBO composition

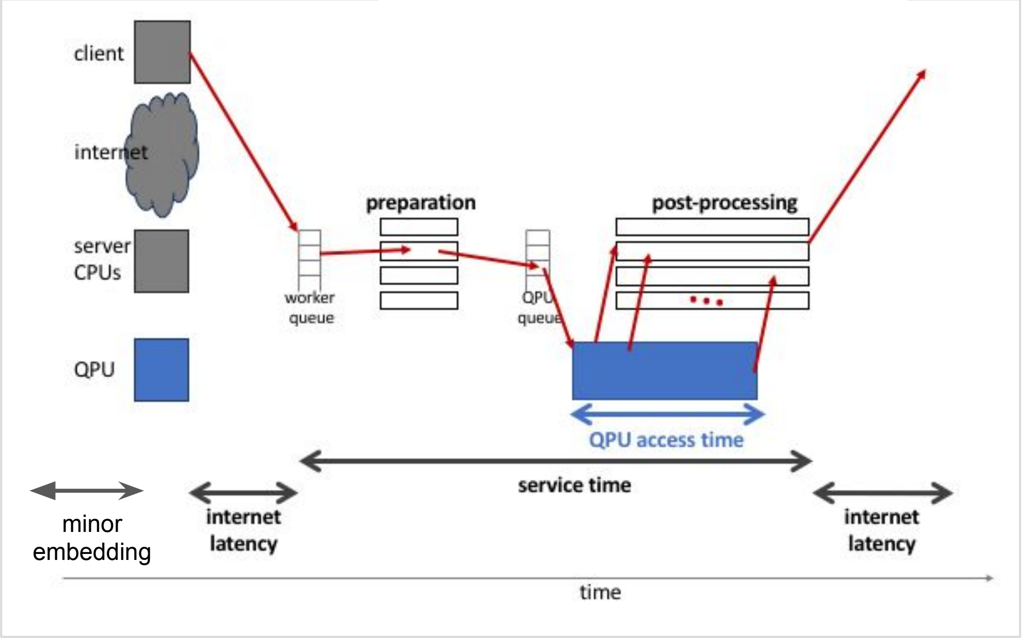


D-Wave timing



QPU access time:





A slightly different approach

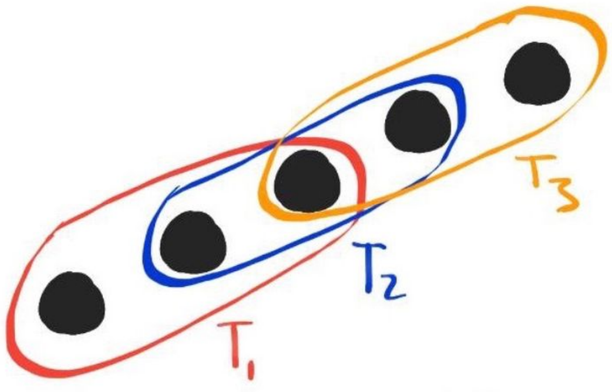
Triplets combined three-by-three.

Model A

In the QUBO, use the same formula for the coupling T1-T2, but a new formula based on the stdev for T1-T3 (+ sum multiple scores): ~ +5% precision on a 60%-dataset.

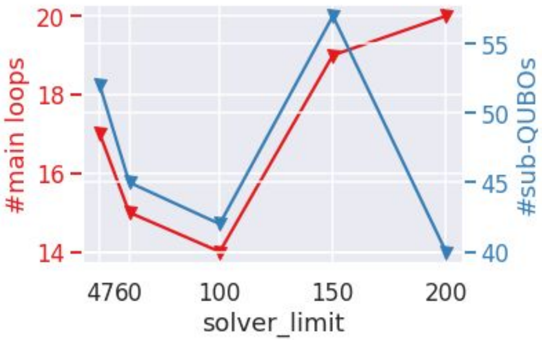
Model B

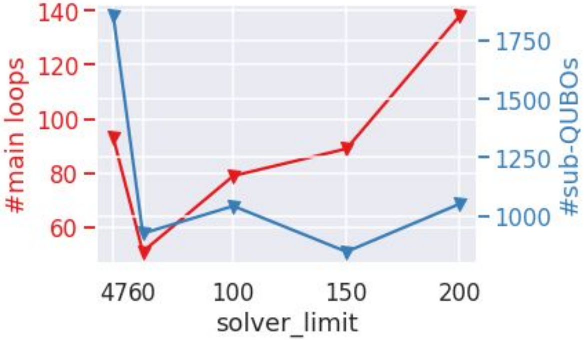
Use the stdev formula for all pairs: ~ +15% precision on a 60%-dataset.

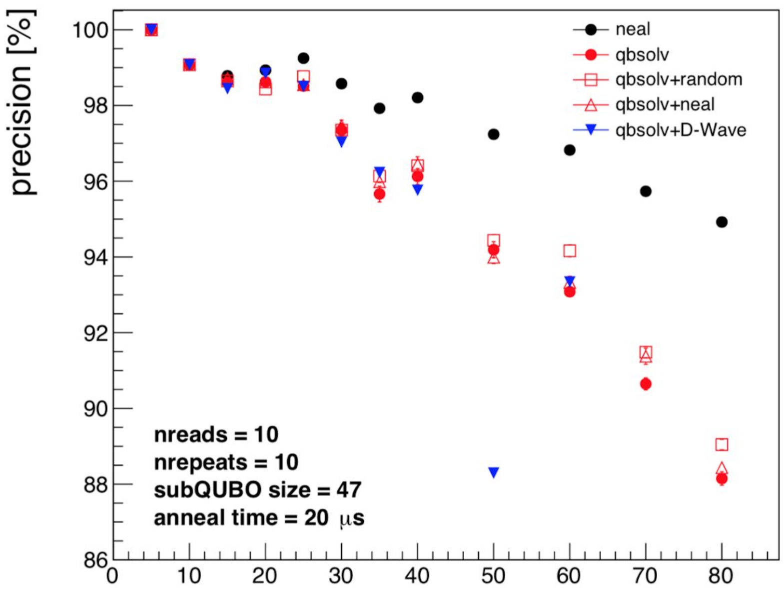


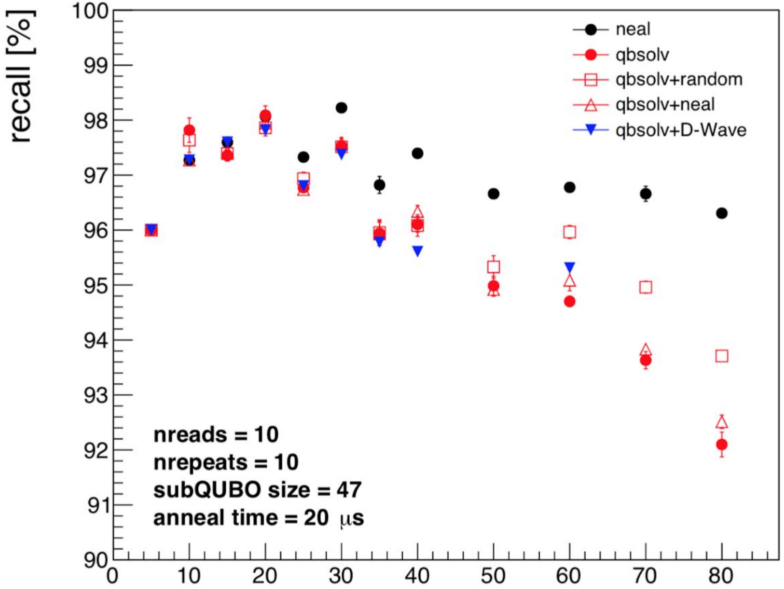
Credits: Alex Smith

qbsolv



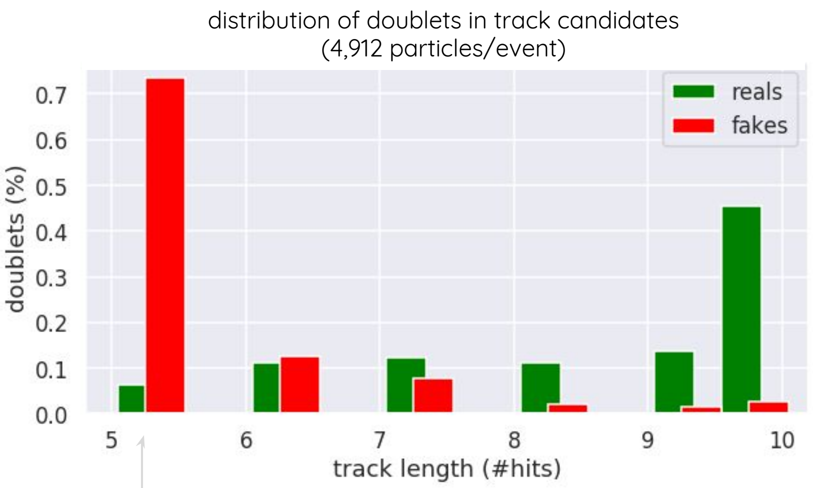


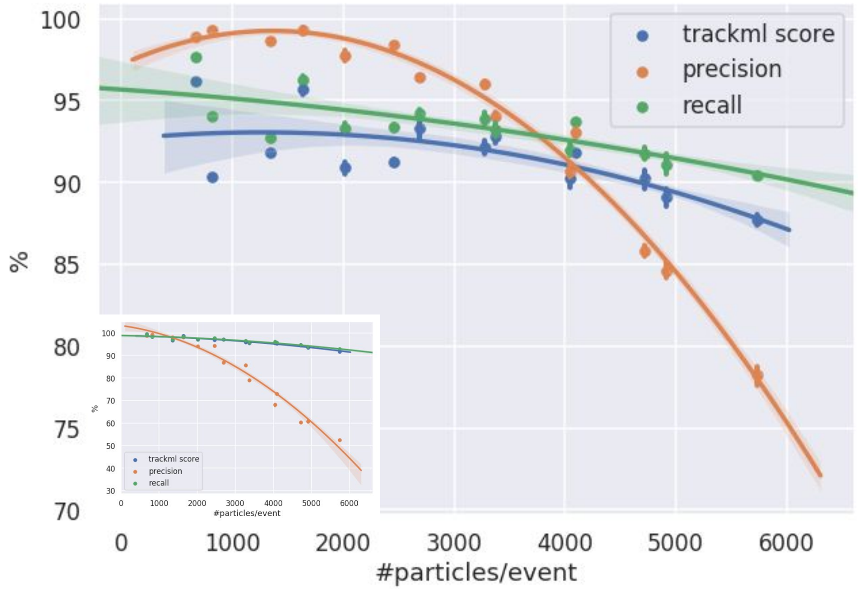




Credits: Koji Terashi

Should we discard small tracks ?



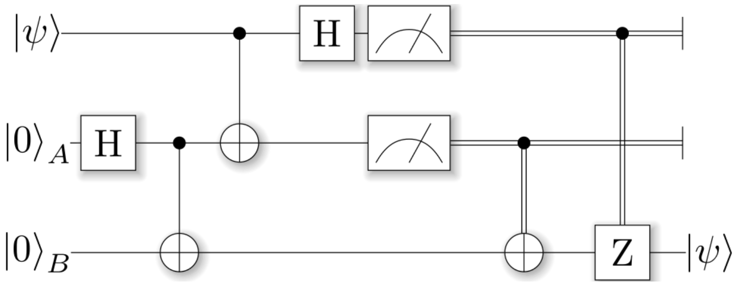


Scores after removing all tracks with 5 hits from the output.

State of Quantum Computing & HEP.QPR

Universal quantum computers

quantum circuits



IBM 50Q

Rigetti 19Q

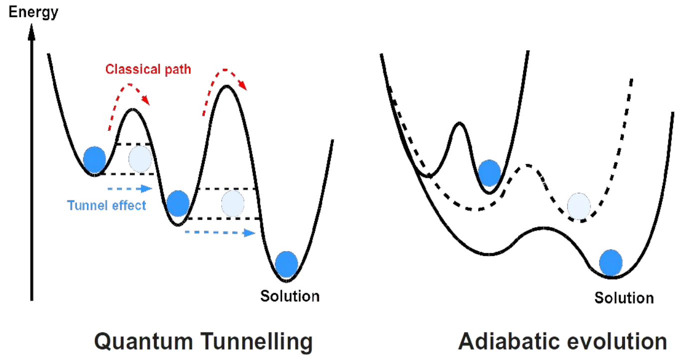
Intel Tangle Lake (49Q)

Google Bristlecone (72Q)

...

» arXiv:1902.00498 «

Quantum annealers



D-Wave (2000Q)

» arXiv:1902.08324 «