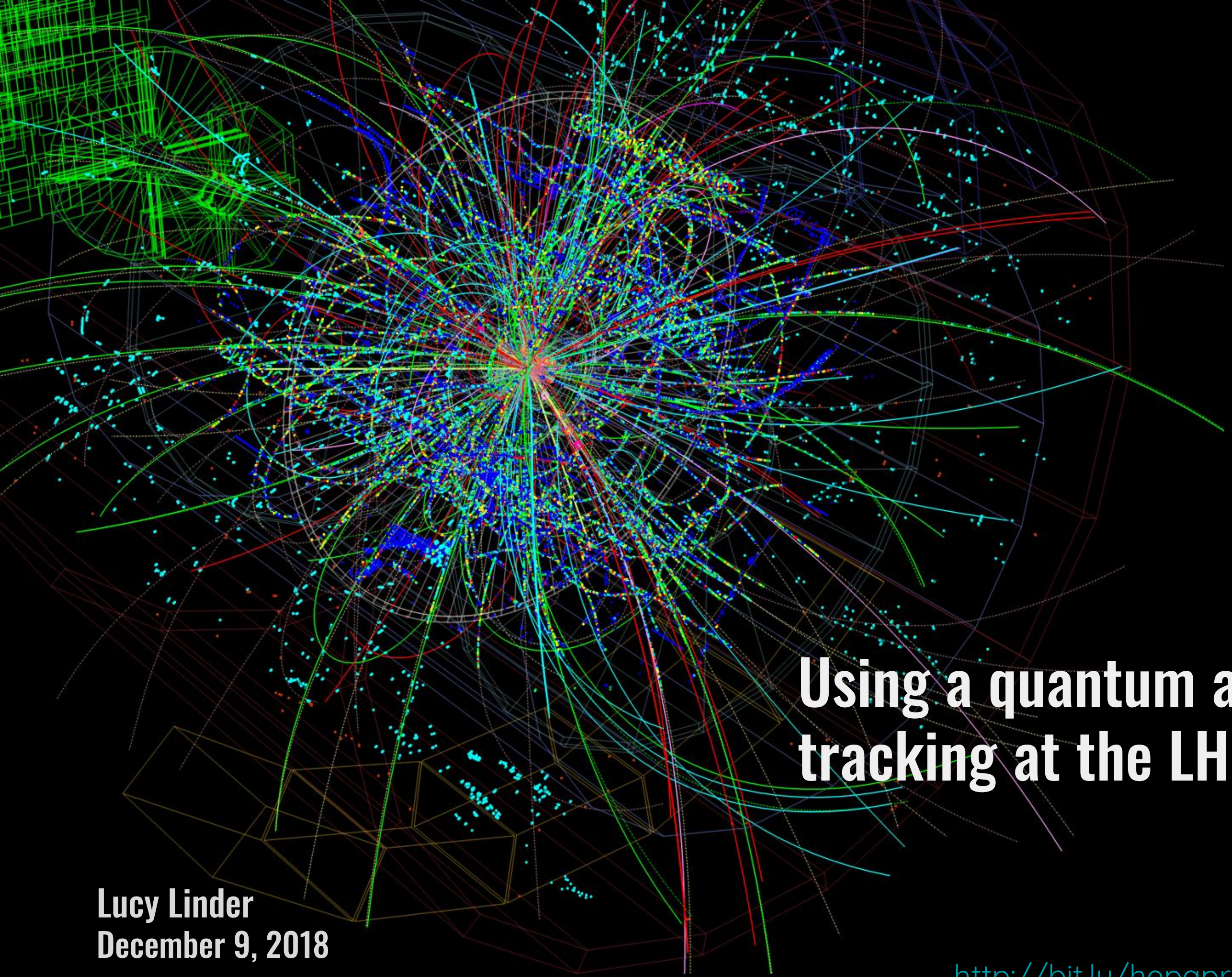


Using a quantum annealer for particle tracking at the LHC

Lucy Linder
December 9, 2018

BERKELEY LAB

U.S. DEPARTMENT OF ENERGY
Office of Science

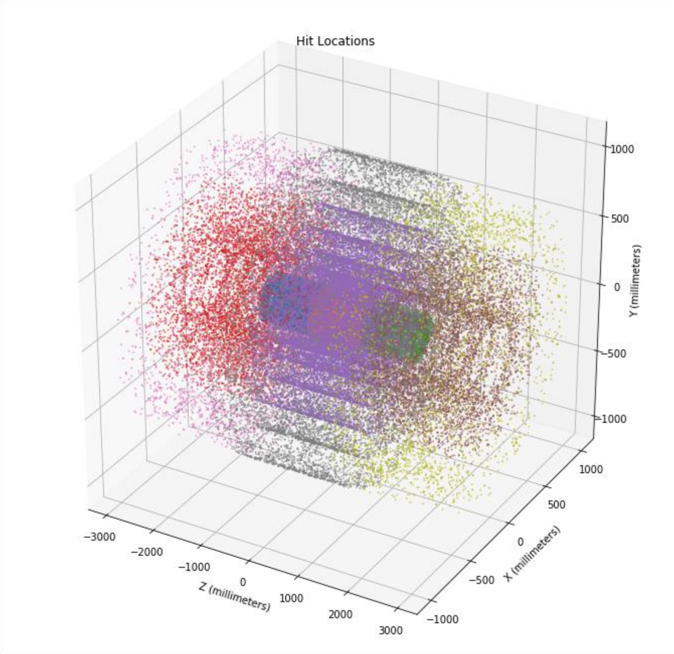
Hes·so
Haute Ecole Spécialisée
de Suisse occidentale
Fachhochschule Westschweiz
University of Applied Sciences and Arts
Western Switzerland

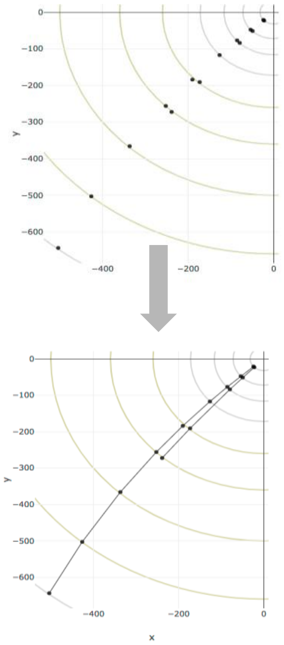
http://bit.ly/hepqpr-cpad

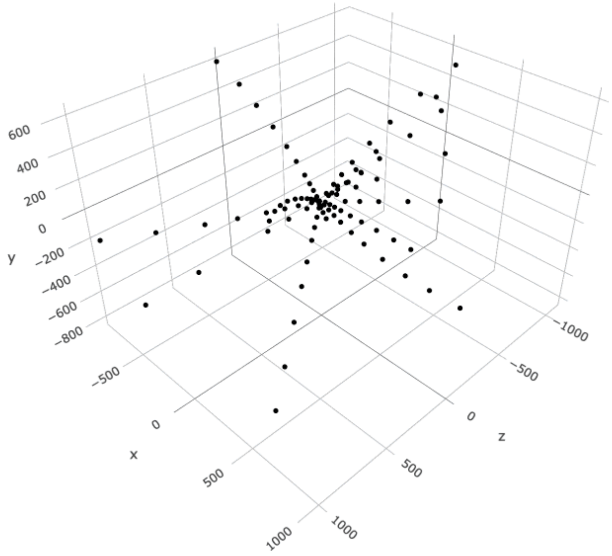
Introduction

Particle tracking in HEP experiments

Pattern recognition	from measurements (*hits*) to reconstructed particle trajectories (*tracks*).
Track fitting	determine the parameters of the particle trajectory from a set of hits.

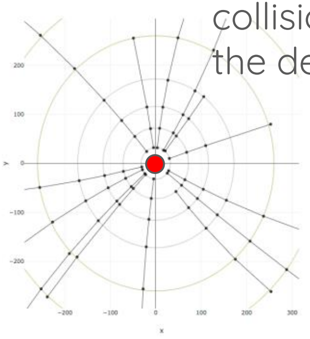


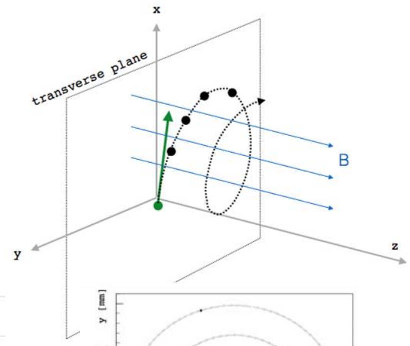




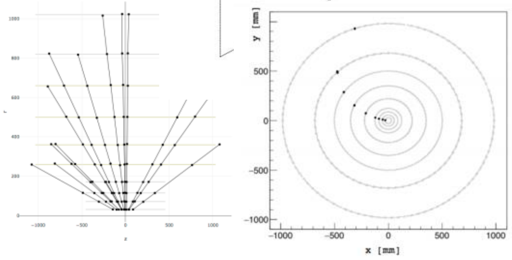
Why is tracking hard ?

collisions at the center of the detector





perfect solenoid magnets…

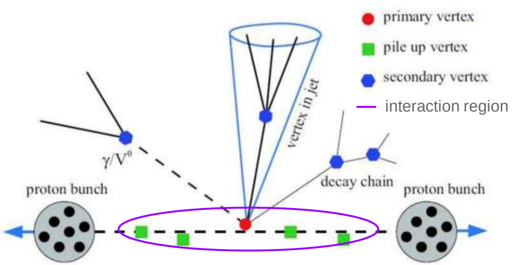


…helices in X-Y, straight lines in R-Z

complete tracks, good measurements

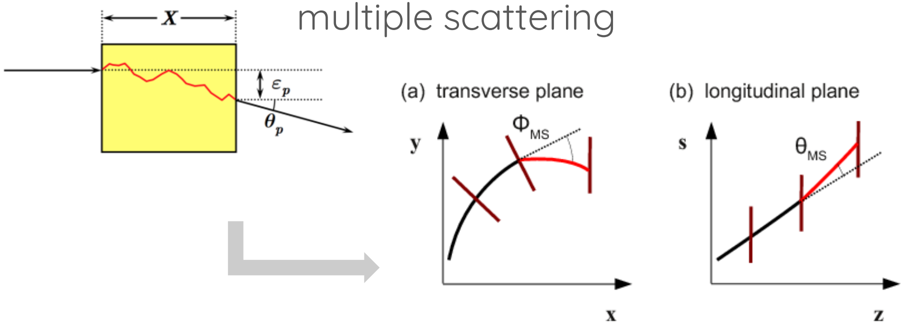
perfect world

real world

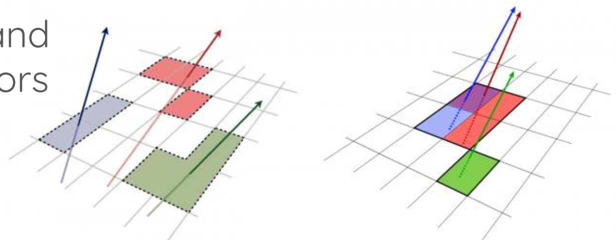


hard scattering, secondary vertices, decay…

multiple scattering



holes, double hits and measurements errors



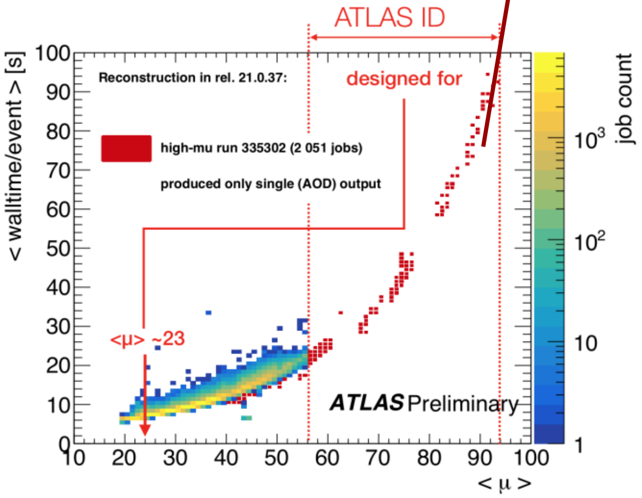
→ algos complex and imperfect !

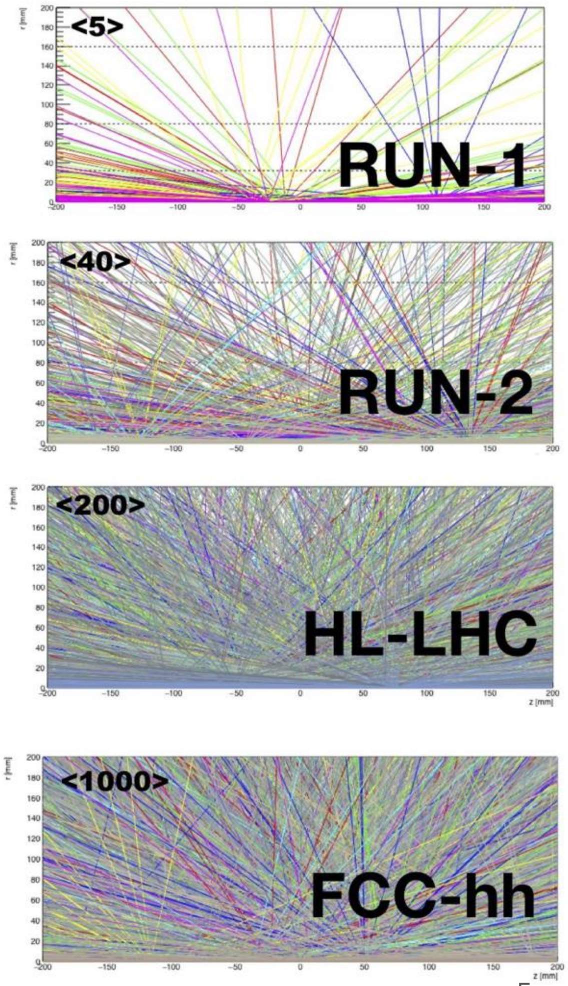
New challenge: HL-LHC

2026: HL-LHC (High-Luminosity-LHC)

- increased event rates (up to x10)
- more complex events (up to μ=200, better detector)

Current algorithms of [at least] *quadratic* complexity: O(N²), N=hits





μ (mu): *the average number of visible pp interactions per bunch crossing*

HEP.QPR, Quantum Pattern Recognition

A DOE-HEP QuantISED pilot project

HEP.QPR goals

Real-time Tracking with Quantum Associative Memory

Track Finding with Quantum Annealing

CHEP 2018

rest of this talk

→ https://hep-qpr.lbl.gov/ ←

Meet the team

Heather Gray (PI)

Frédéric Bapst

Wahid Bhimji

Paolo Calafiura

Steve Farrell

Wim Lavrijsen

Lucy Linder (that's me)

Illya Shapoval

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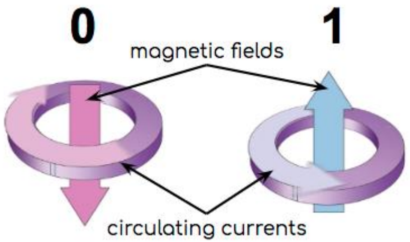
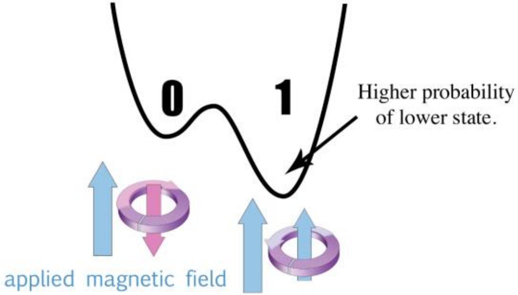
Quantum Annealing & D-Wave

QA in D-Wave computers

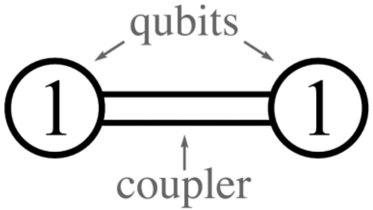
source: dwavesys on YouTube



qubits ⇒ q_i



bias weights ⇒ a_i

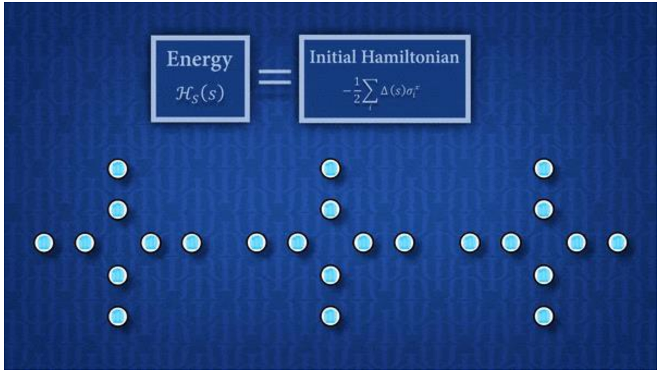


coupling strength ⇒ b_{ij}

quantum machine instruction (QMI) objective function:

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

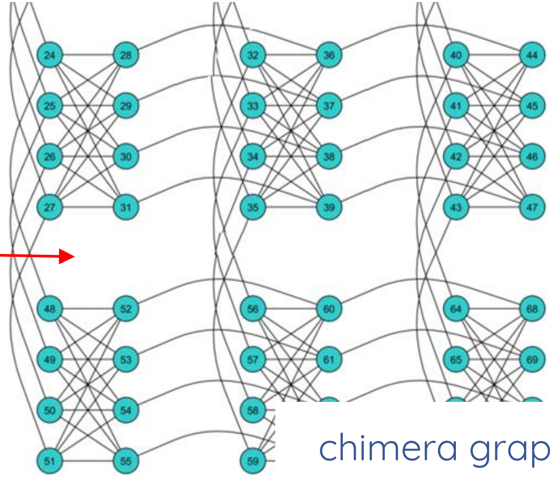
QUBO
Quadratic Unconstrained Binary Optimisation



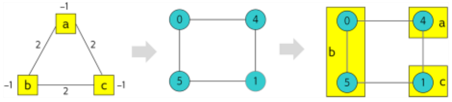
anneal time ~20μs

The D-Wave hardware

	D-Wave One	D-Wave Two	D-Wave 2X	D-Wave 2000Q
Release date	May 2011	May 2013	August 2015	January 2017
Code-name	Rainier	Vesuvius	?	?
Qubits	128	512	1152	2048
Couplers[54]	352	1472	3360	6016
Josephson junctions	24,000	?	128,000	128,000
Operating temperature (K)	?	0.02	0.015	0.015
Power consumption (kW)	?	15.5	25	25
Buyers	Lockheed Martin	Lockheed Martin	Lockheed Martin	Temporal Defense Systems
		Google/NASA/USRA	Google/NASA/USRA	Google/NASA/USRA
			Los Alamos National Laboratory	

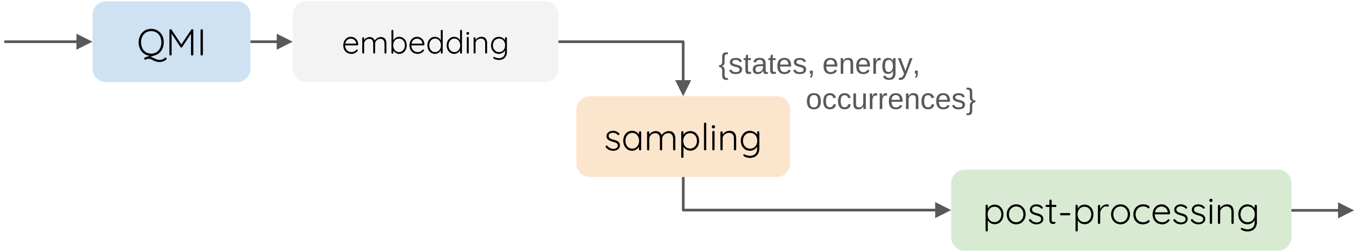


chimera graph



minor embedding

D-Wave recap



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".

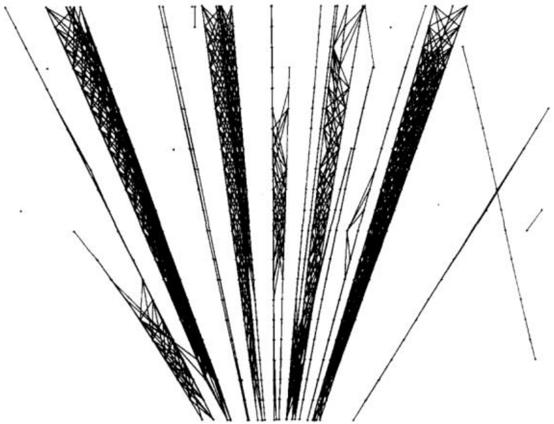


Fig. 2. Display of all generated lines for a real $Z^0 \rightarrow$ hadrons (RZ projection).

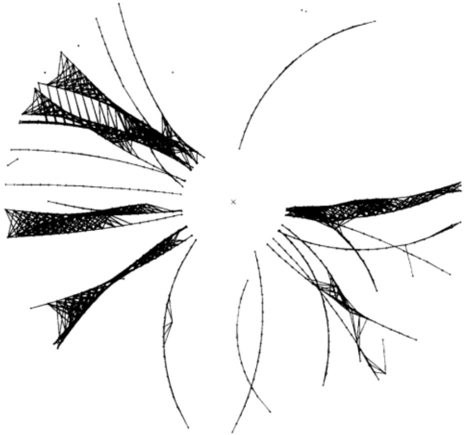


Fig. 1. Display of all generated lines for a real $Z^0 \rightarrow$ hadrons (XY projection).

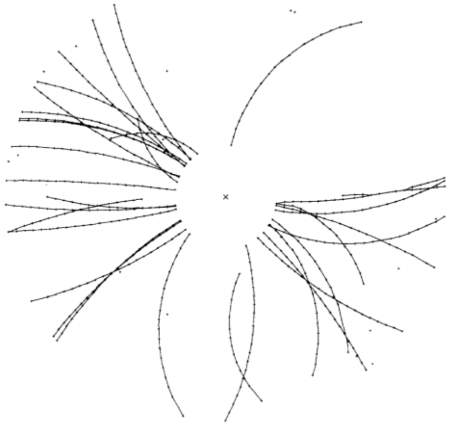


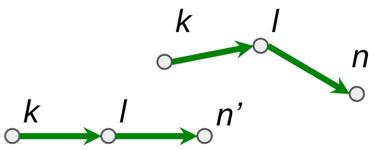
Fig. 3. Display of the activated lines after convergence for a real $Z^0 \rightarrow$ hadrons (XY projection).

source: fast track finding with neural nets

1. generate the set potential doublets (apply early cuts)
2. *binary classification task* to determine which doublets should be kept in the solution

Stimpfl-Abele & Garrido (1990) *ref*

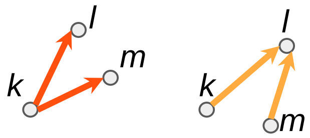
Energy function of the Hopfield Network:



"***connection strength***", interest of connecting two doublets

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

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



activate only the expected number of neurons (N_a)

$$T_{kln} = \frac{cos^{\lambda}\theta_{kln}}{d_{kl} + d_{ln}}$$

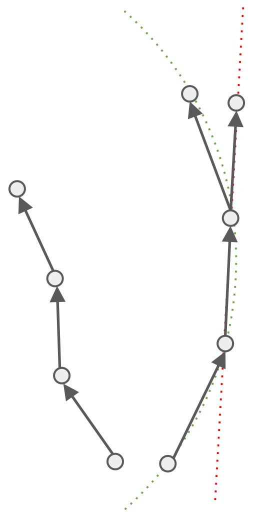
favour short and almost straight connections

parameters: λ α β

Stimpfl-Abele & Garrido (1990) *ref*

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

- "easy" to adapt to a QUBO / QMI
  - set the qubit bias weights **a_i** to 0
  - set the coupling strength **b_i** to either a connection strength (T) or a conflict constant (α term)
  - drop the β term
- but…
  - efficient early selection of doublets need an *origin assumption*
  - "*favor straight connections*" …
  - no "continuity" between doublets → zigzag patterns



OK for high P_T tracks only,

breaks on dense datasets (> 400 particles/event)

From doublets to triplets

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

Two triplets $T_{a,b,c}$ and $T_{d,e,f}$ can be combined:

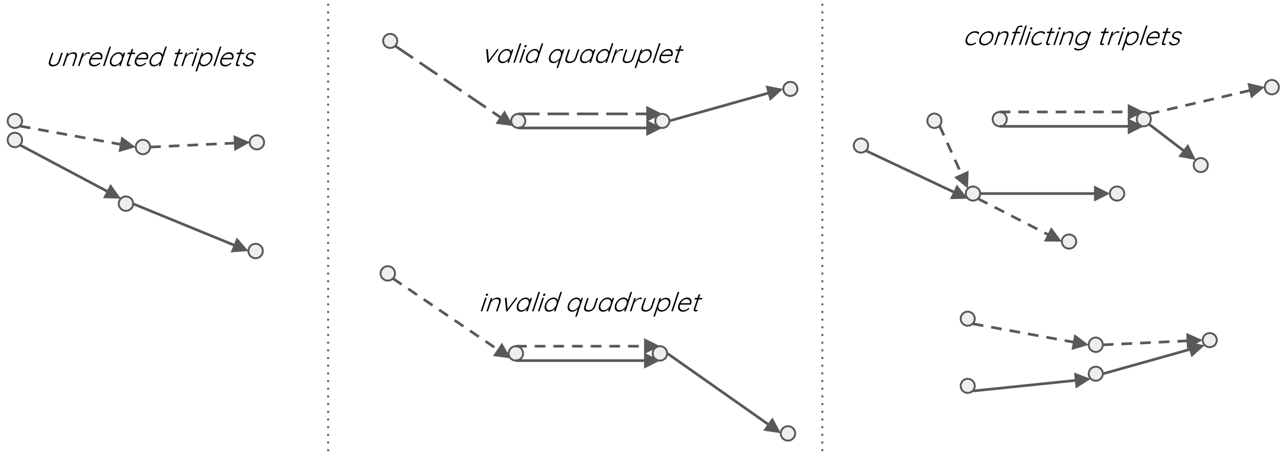
- into a quadruplet (qplet) if $a{=}d \wedge b{=}e$

If they share any other hit, they are in conflict.

New properties:

- curvature in the transverse plane
- delta angles in the R-Z plane
- …

→ Powerful early selection,
better continuity, fewer zigzags



The new energy function

Stimpfl-Abele

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

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

prior "*bias weight*"

"*connection strength*", interest of qplet T_i-T_j

avoid "*conflicts*"

The new energy function

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

As a QUBO:

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

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

Underlying math

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

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

A triplet $T_{a,b,c}$ is more interesting 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 qplet (T_i, T_j) is more interesting 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 qplet 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 smaller chunks.

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

Set weight=0 for particles with:

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

endcaps
double hits

tune the model for that !

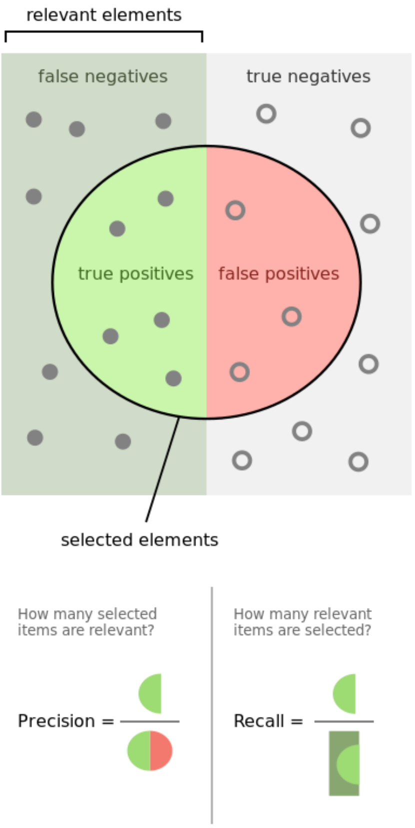
Input / output

→ set of potential doublets.
Python adaptation of the ATLAS online seeding GPU code (prototype).

← subset of the input, doublets part of track candidates.

Scoring functions

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



false negative = missings
false positive = fakes

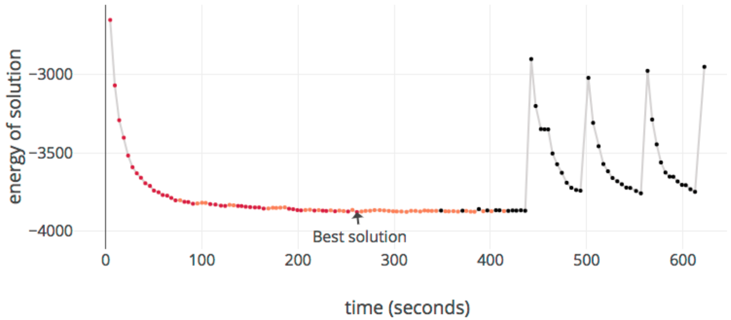
QUBO solver

iterative hybrid classical/quantum algorithm

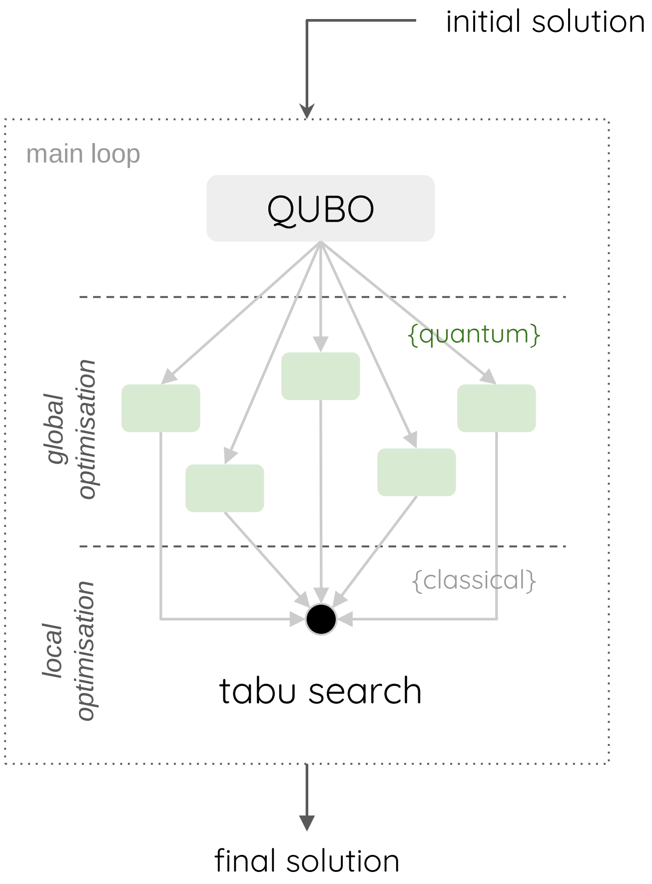
QBSOLV

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

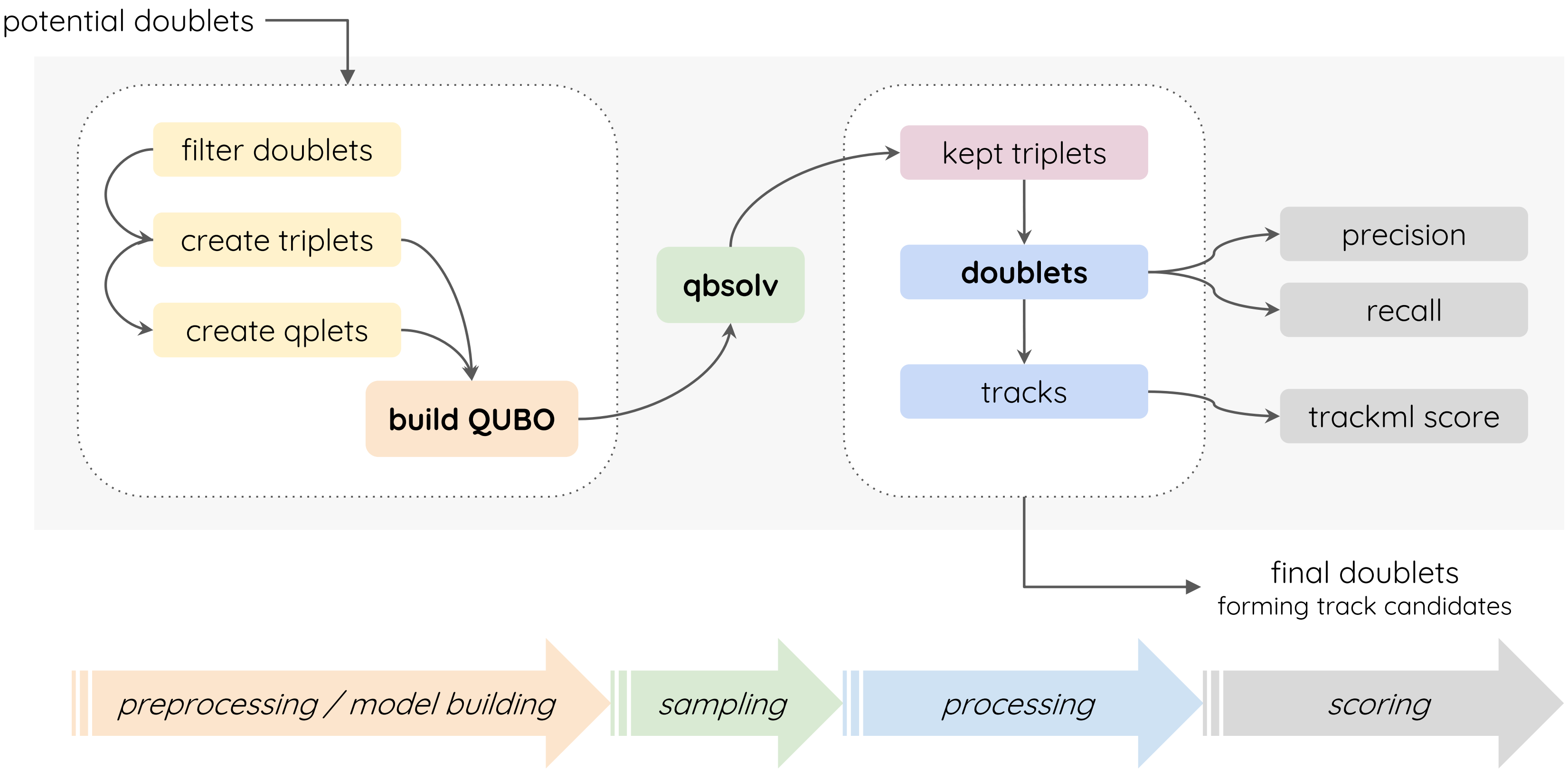
Tabu search on the recomposed solutions.



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



Algorithm overview

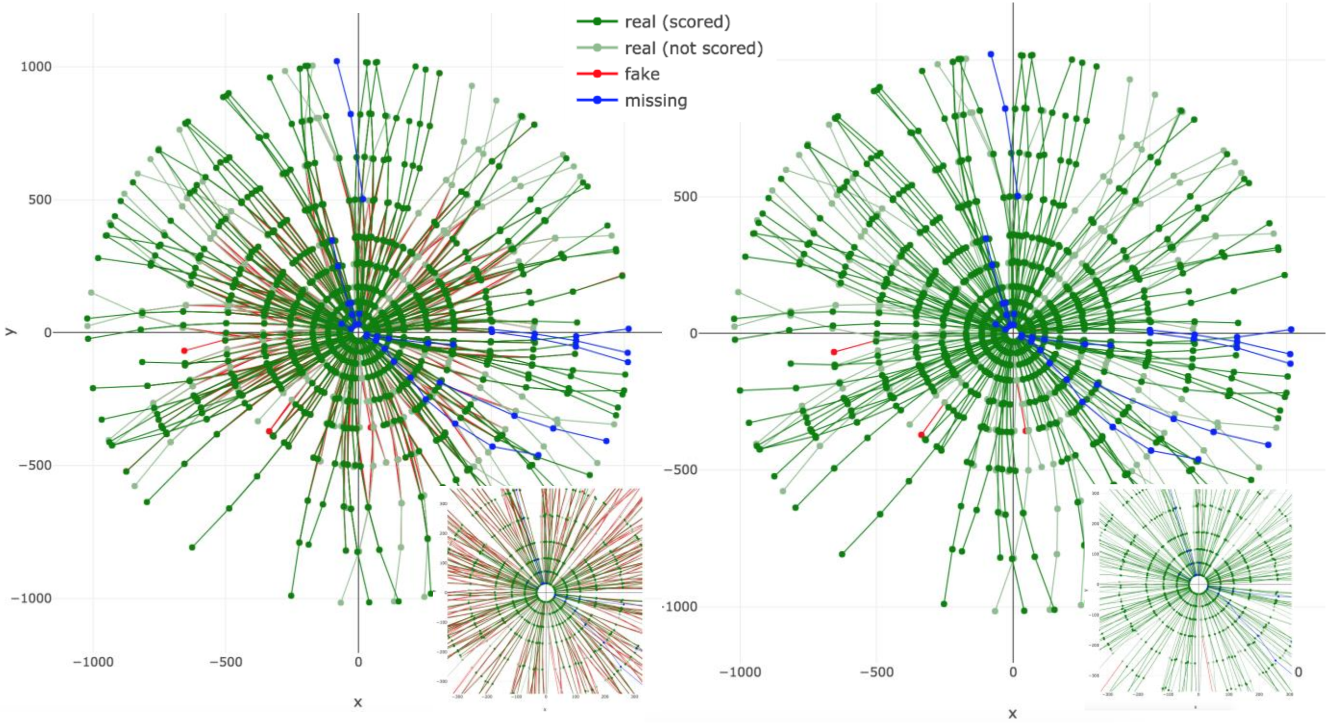


Results

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

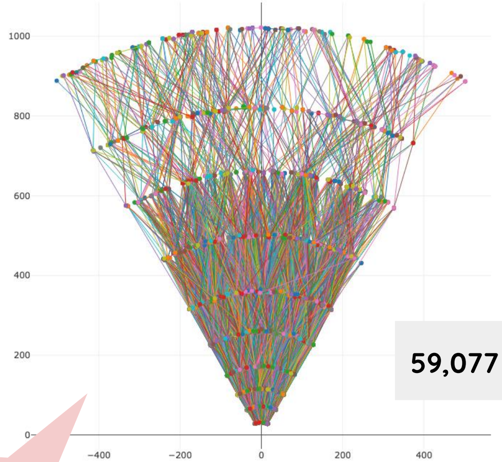
1,512 doublets
p=**99.13**%, r=**97.06**%

trackml score **97.55**%

Performances at low Pt

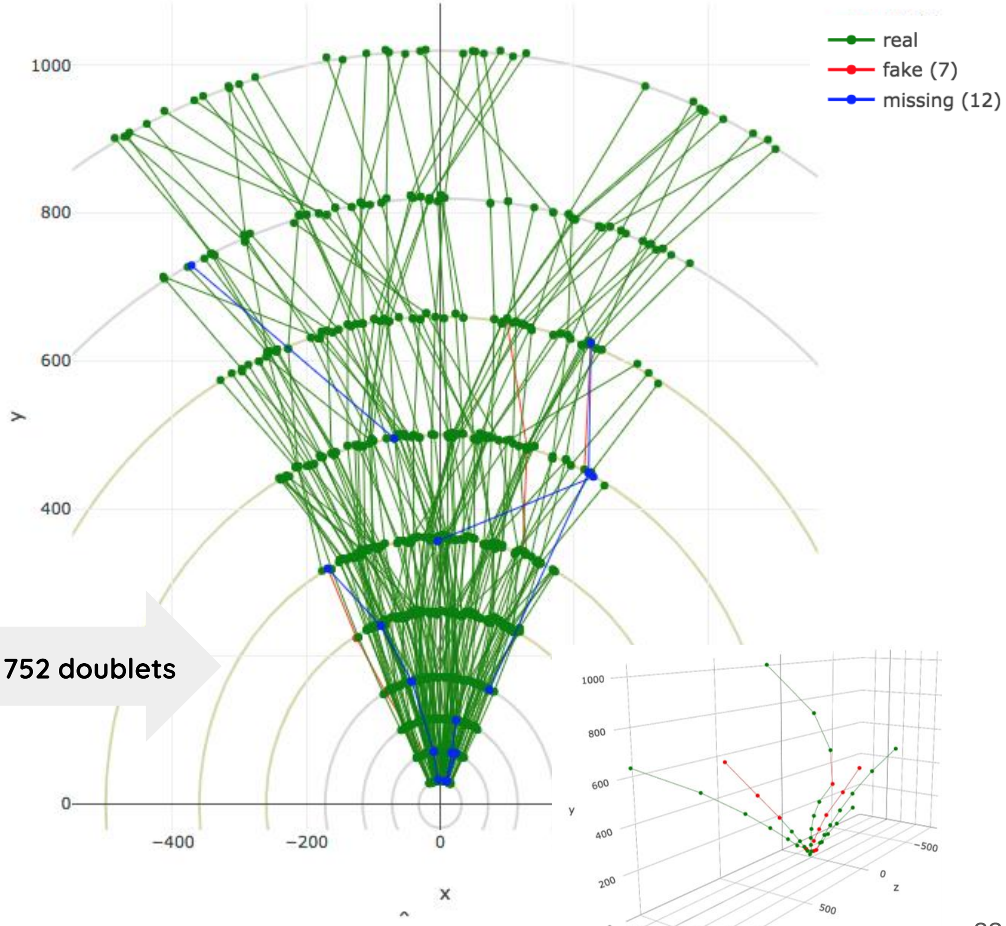
186 particles in a phi slice of π/3

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



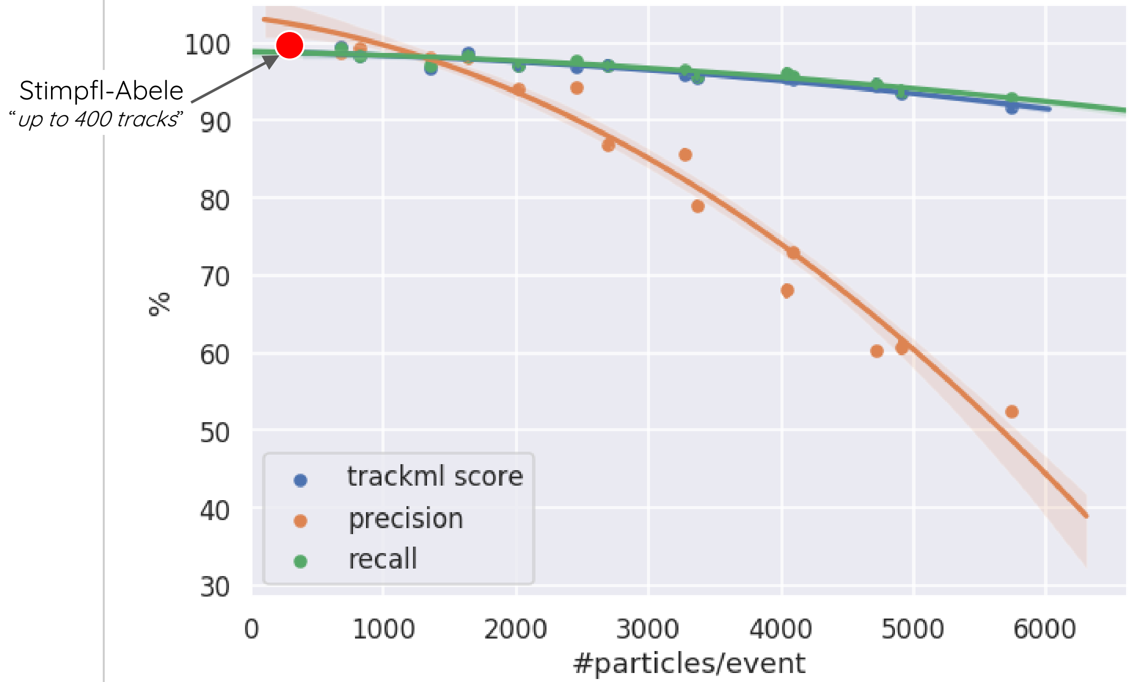
QUBO size
68,043

59,077 ⇒ 752 doublets

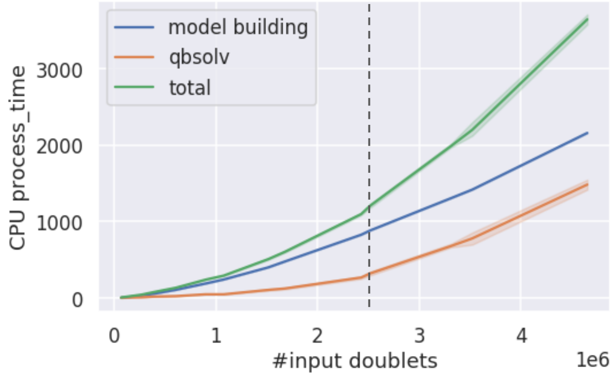


Performance

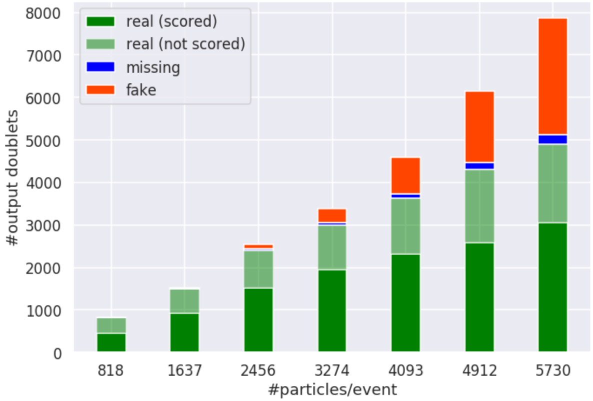
Full TrackML event 6,900 - 14,000 particles, Pt ≥ 150 MeV, ~15% noise/lower Pt hits



time scales ?quadratically? with the #input doublets



composition of the final doublets



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

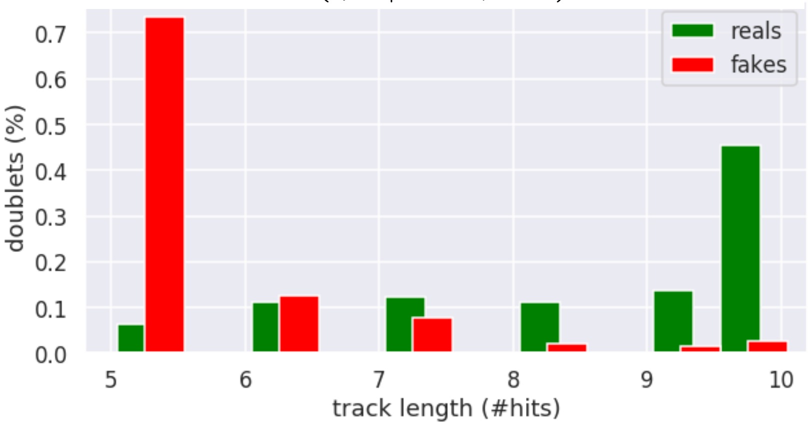
What about the fakes ?

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

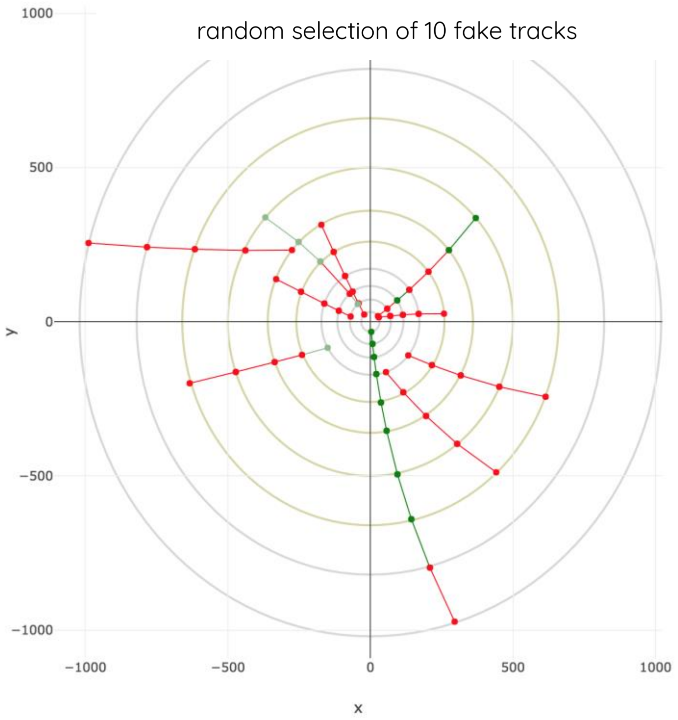
soft constraints and very simple geometrical constants is not as good as a sophisticated algorithm based on hard constraints (fits)".

Stimpfl-Abele & Garrido, fast track finding with neural networks

distribution of doublets in track candidates
(4,912 particles/event)



random selection of 10 fake tracks



→ using track fitting methods in a post-processing step *should* let us filter many fakes

Future work

improvements & tuning

- hyperparameter + code optimization
- reduce fake tracks at high track density
- include more properties e.g. magnetic field, CoV

benchmarks & speedup

D-Wave
Fujitsu digital annealer
other QUBO solvers

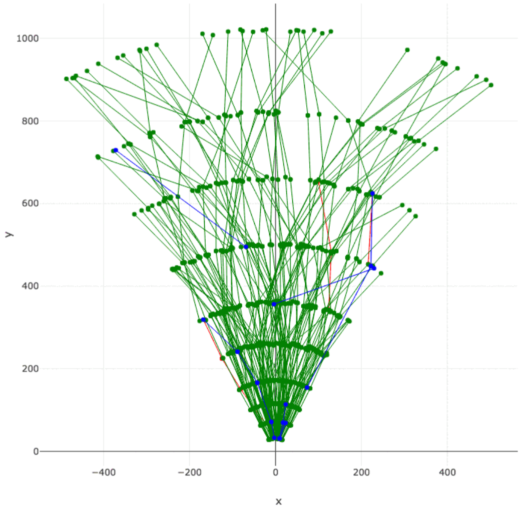
- study physics performance
- study timing performance

tests

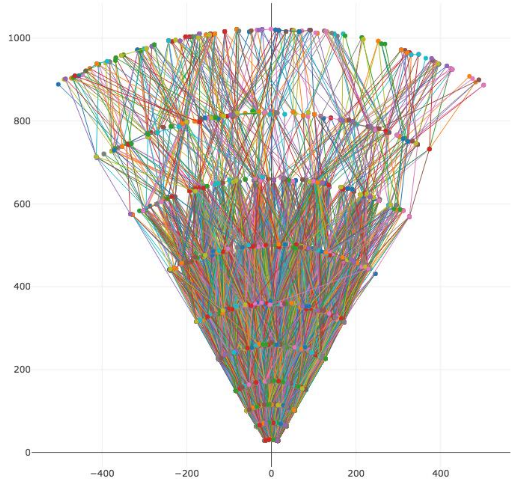
- bigger datasets
- noise level

Thank you for your attention

Any questions ?



Any questions ?



backup slides

Basics of QA

adiabatic theorem of quantum mechanics,

a physical system remains in the ground state if { perturbations are slow; there is a gap }

QA recipe:

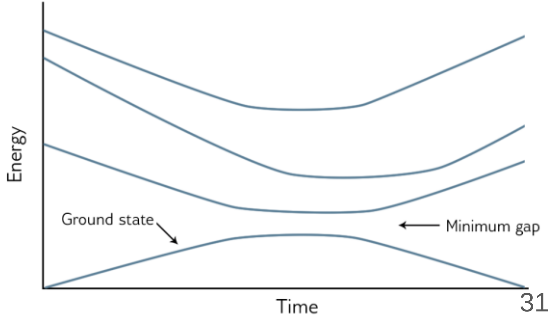
initial Hamiltonian H_0 → $H(s)=A(s)H_o+B(s)H_p$ with

problem Hamiltonian H_p →

$A(s)\searrow$ and $B(s)\nearrow$ given $s = t/t_f \lesssim 1$ (t_f = *anneal time*)

If the adiabatic conditions are respected,

the system's ground state at $t=t_f$ encodes the solution.



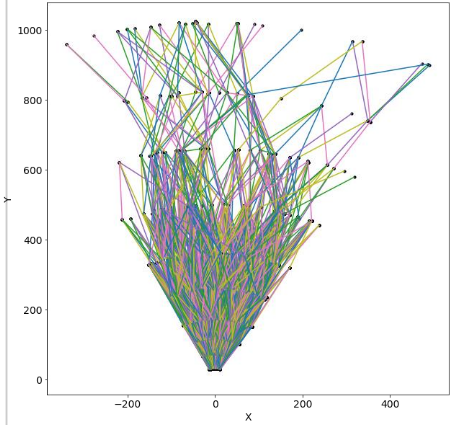
Ising, QUBO, QMI, ...

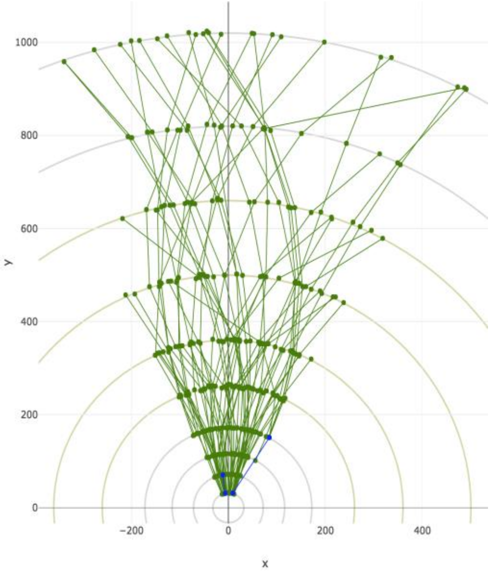
Problem Expression	Terms			
	Linear coefficient	Quadratic coefficient	Variable	States
QUBO (scalar)	a_i	$b_{i,j}$	q_i	$\{0, 1\}$
QUBO (matrix)	$Q_{i,i}$	$Q_{i,j}$	x_i	$\{0, 1\}$
Ising	h_i	$J_{i,j}$	s_i	$\{-1, 1\}$
Graph	Node Weight	Edge Strength	Node	
QPU	Qubit Bias	Coupling Strength	Qubit State	{Spin Up, Spin Down}

More at https://docs.dwavesys.com/docs/latest/c_gs_3.html

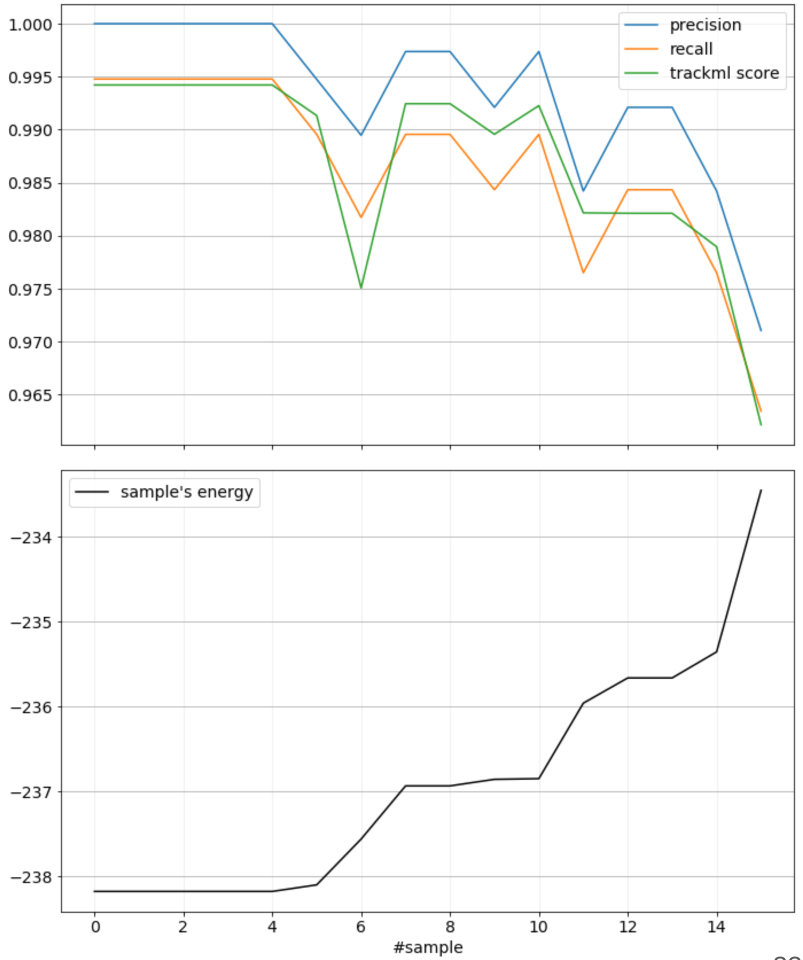
D-Wave run (LEAP)

trackml score of **99.42%** for 60 tracks in a phi angle of π/3 rad.





from 10,952 input doublets down to 380.



D-Wave run (LANL)

2,456 tracks/event (~30%)

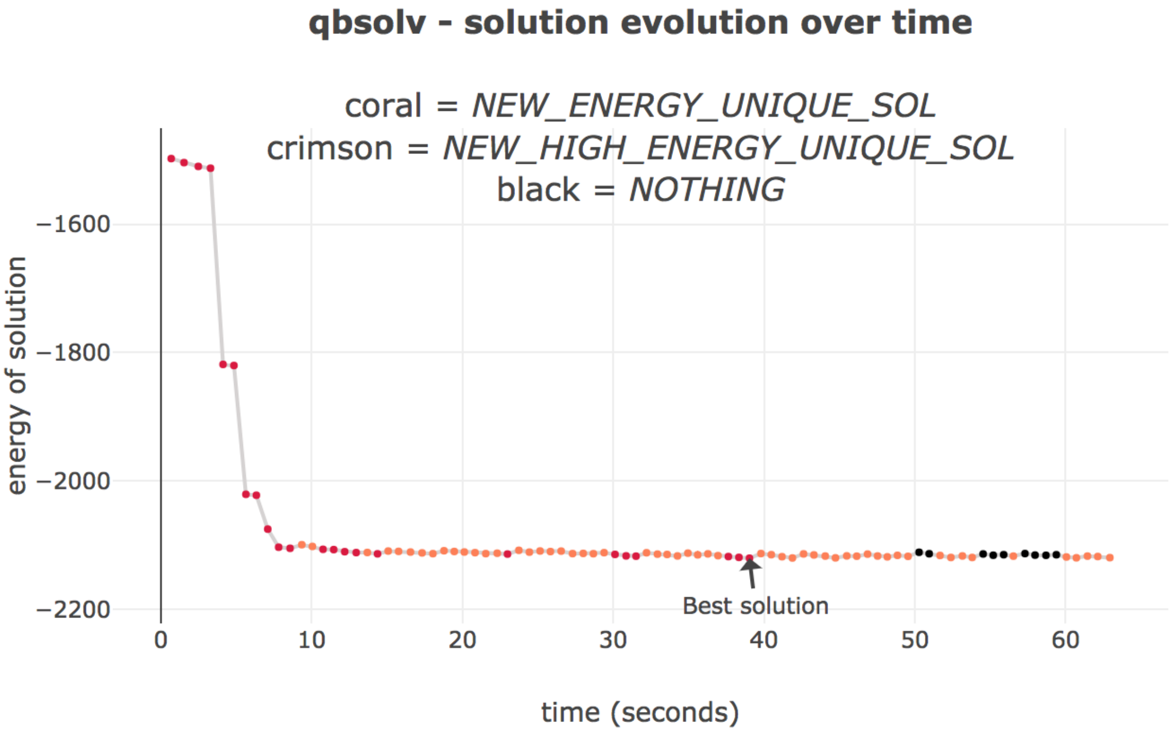
Total subQUBOs submitted: 13,059

```
p=90.2%, r=96.5%
trackml=96%
```

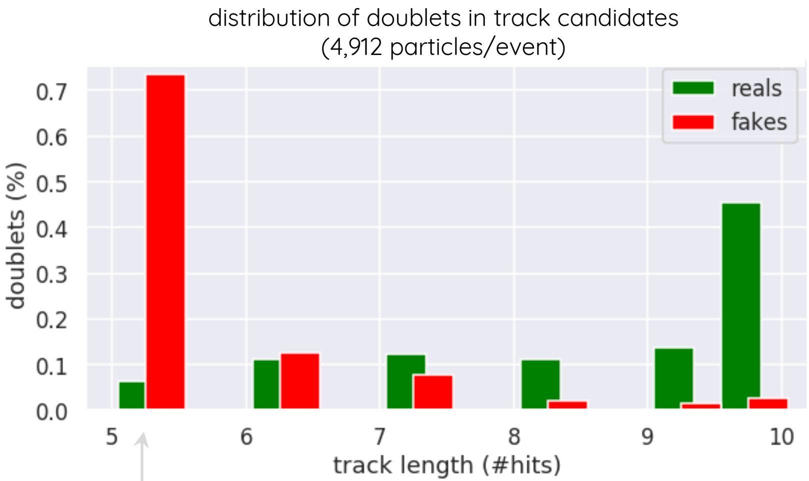
using solver: `DW2X_LANL_1`

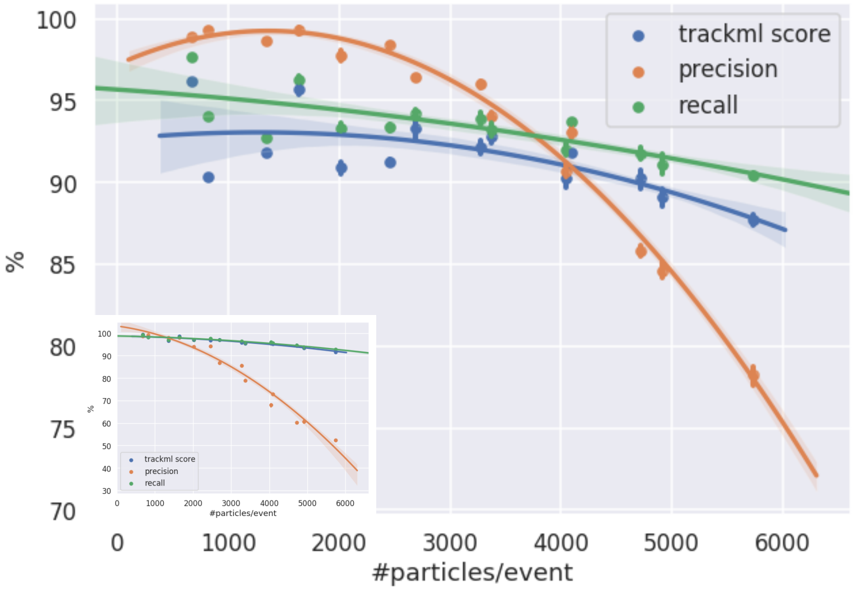
Wall time: 29:20.76

no significant difference with the classical run.



Should we discard small tracks ?



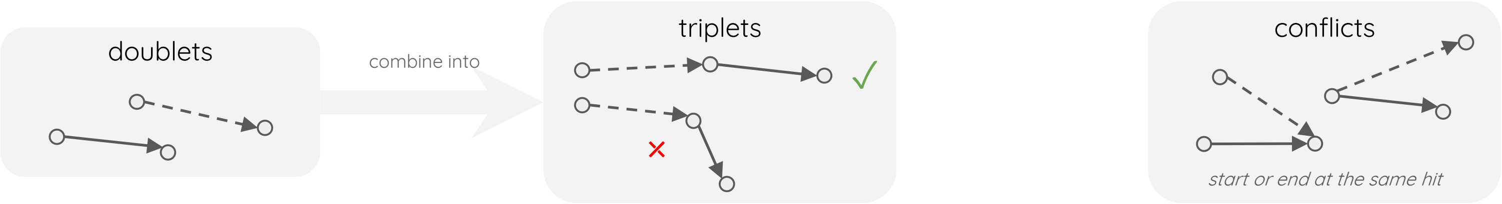


Scores after removing all tracks with 5 hits from the output.

Doublets, triplets, quadruplets, quintets

✓ *valid*, generated by the model
✗ *invalid*, not generated

doublets model (Stimpfl):



triplets model (HEP.QPR):