Quantum Technology Initiative forum: Quantum Computing

Quantum Applications @ LHCb

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Istituto Nazionale di Fisica Nucleare

Outline

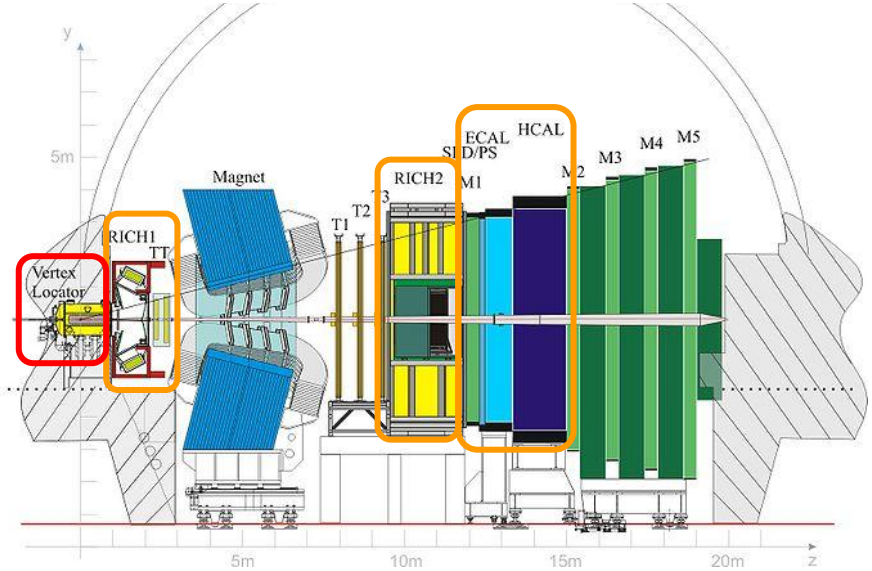
Physics introduction
Physics cases @ LHCb

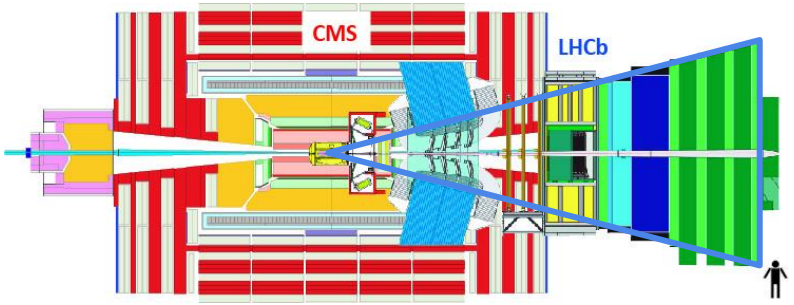
Ongoing work
Quantum Machine Learning for jet tagging

Results and future studies

LHCb

LHCb is a **forward spectrometer** designed to study **flavour physics**





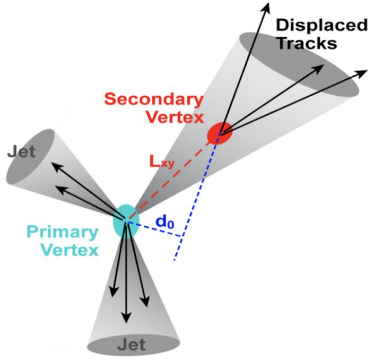
- complementary phase-space region w.r.t. ATLAS & CMS
- excellent vertex reconstruction
- excellent Particle Identification (PID)

Possible Quantum Applications @ LHCb

WIP

- **Jet tagging with Quantum Machine Learning (QML)**

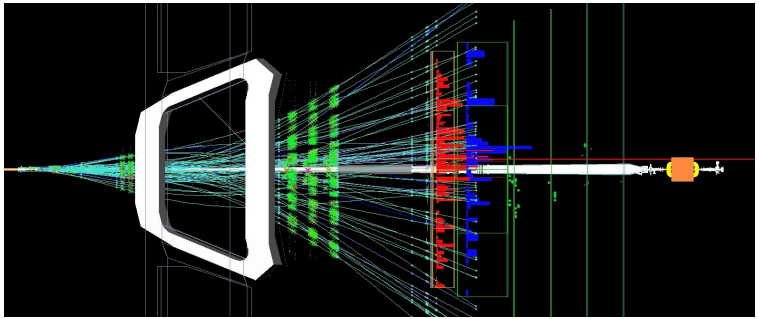
  QML model based on Variational Quantum Circuits (VQC) to perform Jet identification



coming soon

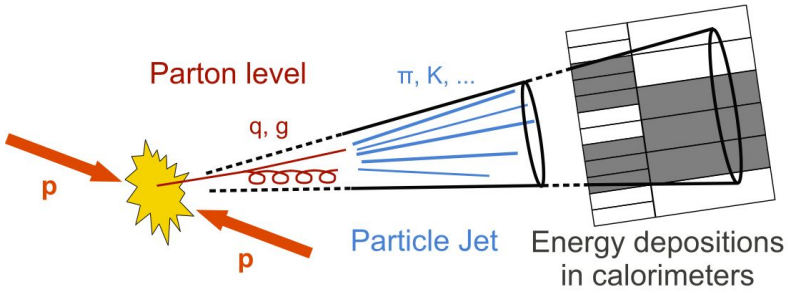
- **Particle tracking with quantum pattern recognition**

  Track reconstruction algorithm based on Quantum Hough Transform (possible quantum speed-up due to reduced complexity)

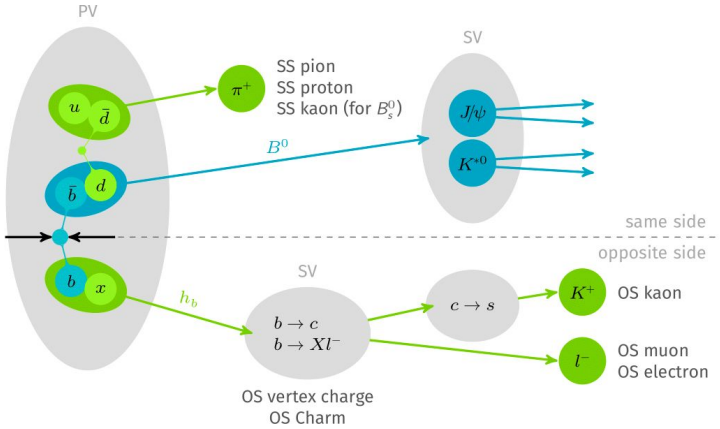


b-jet tagging @ LHCb

@ LHC is **fundamental** to identify the **flavour** of the quark originating the jet → **jet tagging**



"Jets are streams of particles produced by QCD processes in proton-proton collisions"

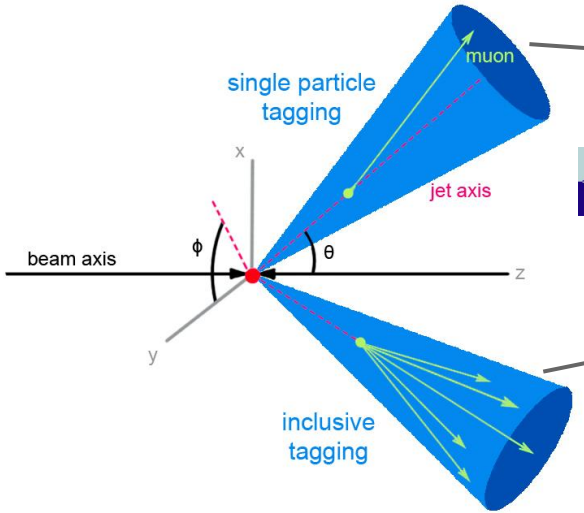


In particular @ LHCb we are interested in studying jets generated by b and b-bar quarks

b-jet tagging

Classical tagging methods

There are two possible approaches to achieve this task: **exclusive** and **inclusive** algorithms



exclusive algorithms use information from a specific process to infer the quark flavour

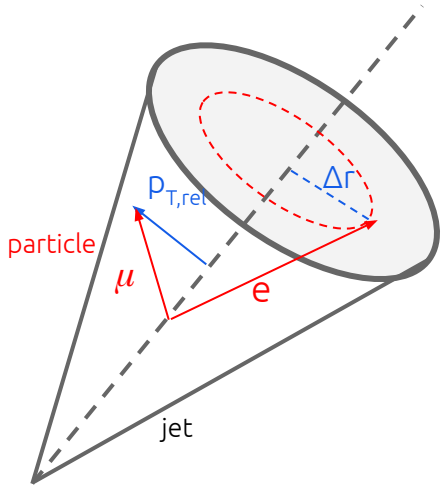
muon tagging: a μ coming from the b (or b-bar) semileptonic decay (P =10%) is used to tag the jet (μ and b charges are correlated)

inclusive algorithms use information from the whole jet substructure

Machine Learning (ML) algorithms such as **Deep Neural Networks** (DNN) and **Tree Tensor Networks** (TTN)

Dataset

Official LHCb simulation of di-jet generated by b and b-bar quarks @ E_{cm} = 13 TeV (Run 2 condition) → ~ 700.000 jets (60% training, 40% testing & evaluation)



Inside each jet we consider 5 types of particles

muon electron pion kaon proton

and for each type we select 3 variables:

- $p_{T,rel}$: transverse momentum relative to the jet axis
- Δr: distance relative to jet axis
- q: charge of the particle

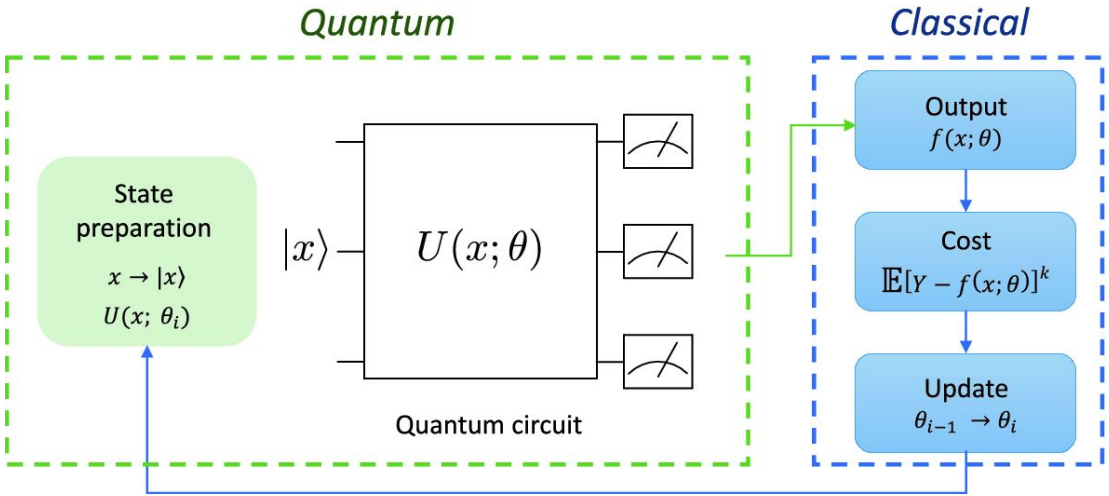
\+ 1 global variable → total jet charge

for a total of 16 input variables

the official LHCb simulation resembles real LHCb data

A quantum approach

classification problem = **Variational Quantum Classifier**



Data are fed into variational quantum circuit.

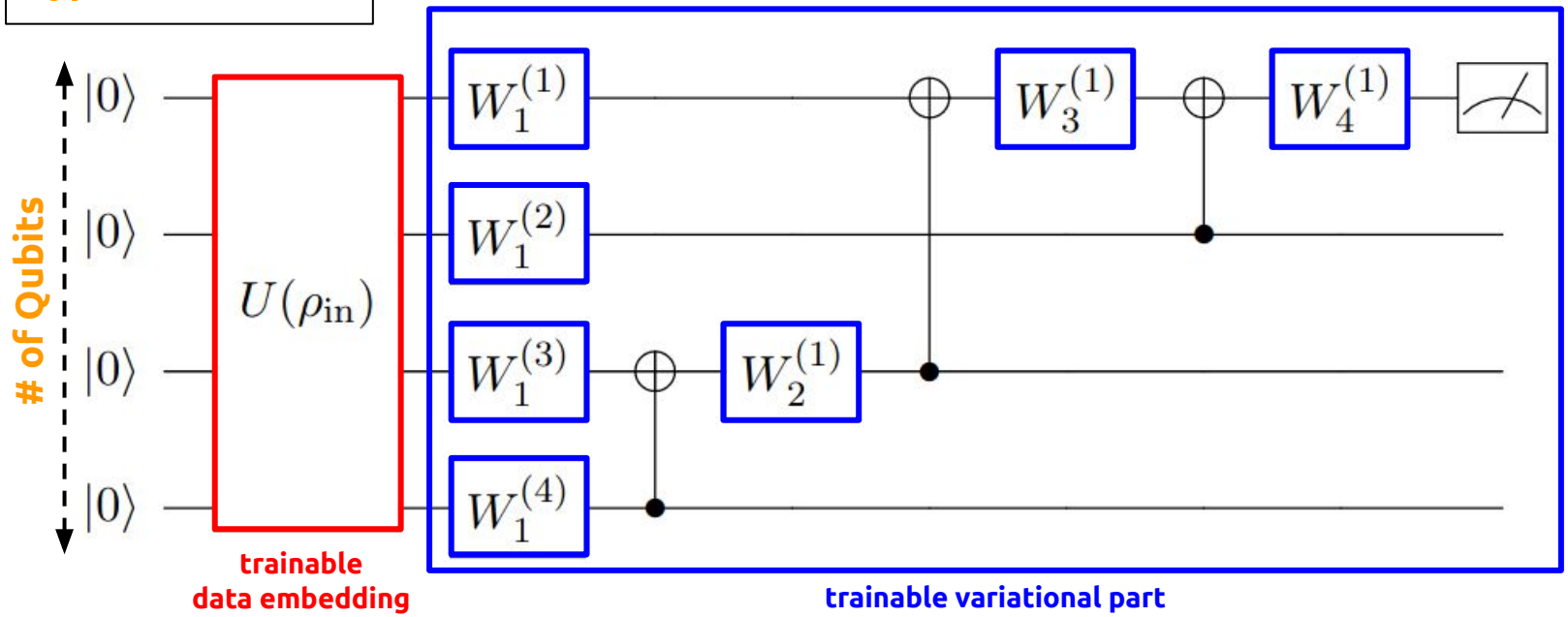
Measurements of qubits are mapped to probabilities for labels.

Probabilities are used to estimate a cost function which is optimized through a classical optimizer

[2011.06258] Toward Trainability of Quantum Neural Networks https://arxiv.org/abs/2011.06258

VQC “a la TN” classifier

Input
Parameters
Hyper-Parameters

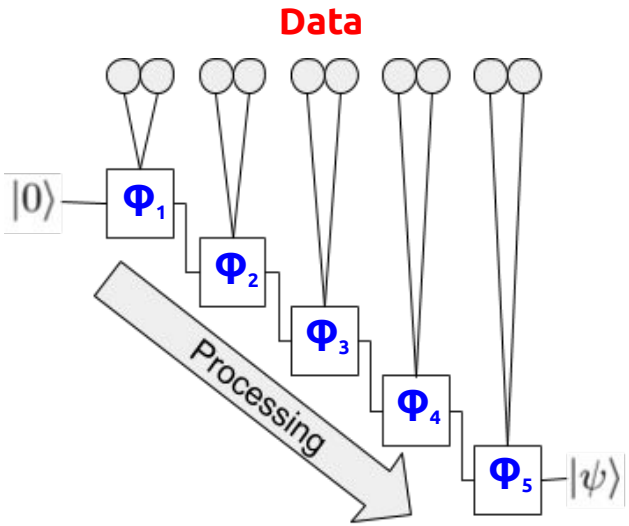


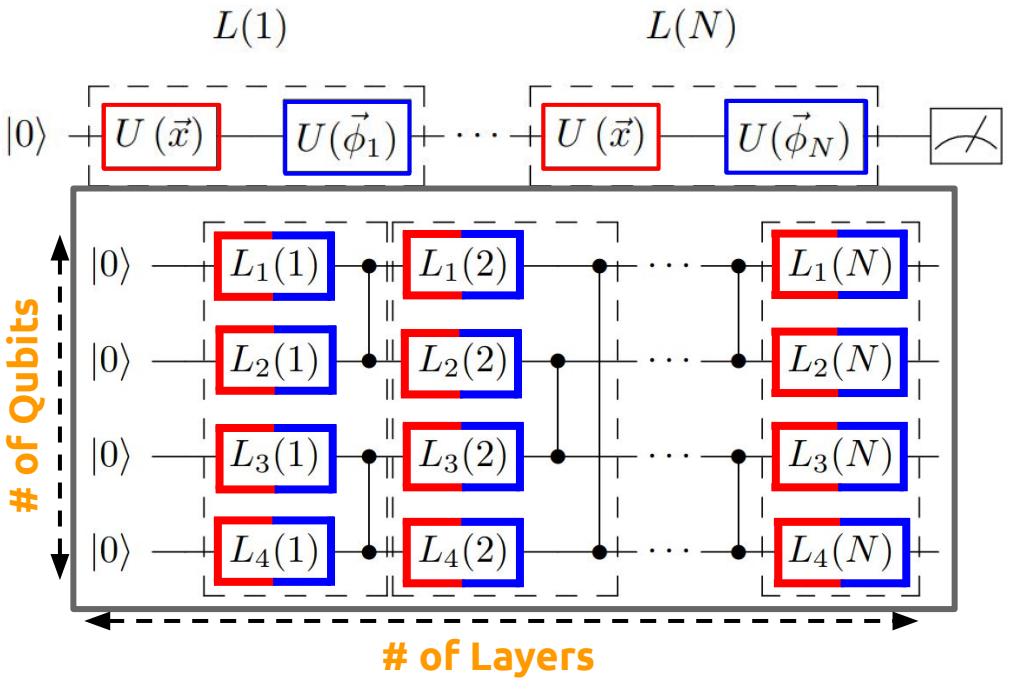
[1907.02085] Data re-uploading for a universal quantum classifier

https://arxiv.org/abs/1907.02085

Data Re-uploading classifier

Input
Parameters
Hyper-Parameters



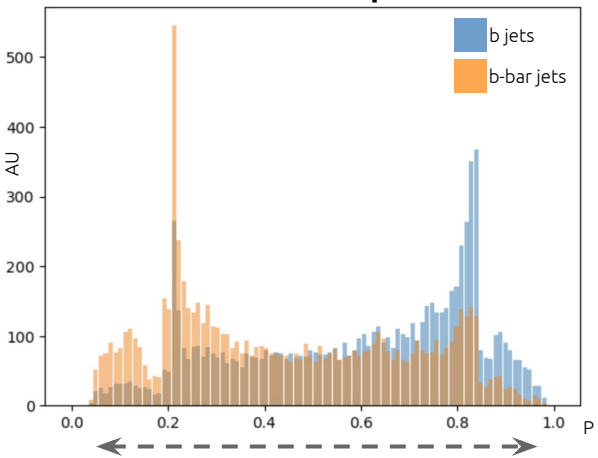


Training results

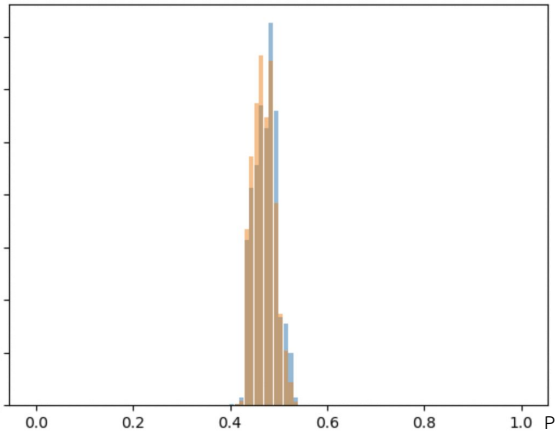
We show some results on training performances for the VQC “a la TN” classifier (similar results for re-uploading classifier)

Probability distribution

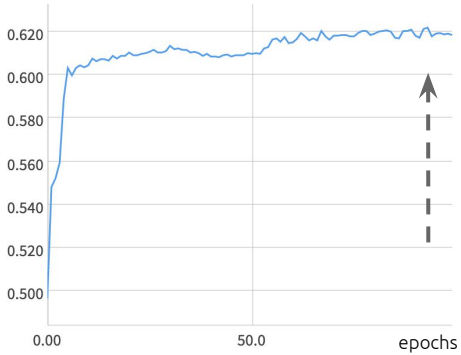
Result for last epoch



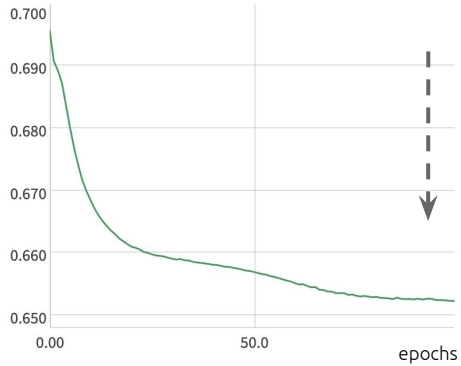
Variations through epochs



Accuracy



Loss

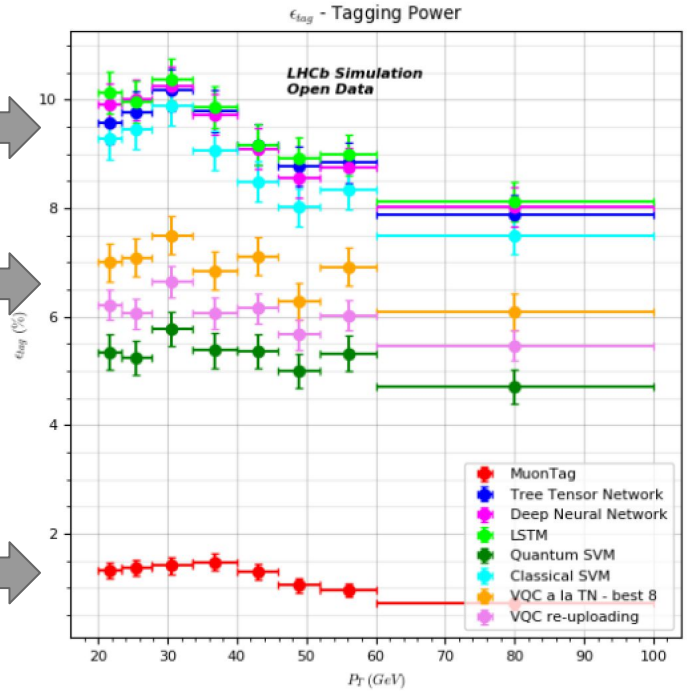


Final (preliminary) results on noiseless simulator

classical

quantum

MuTag



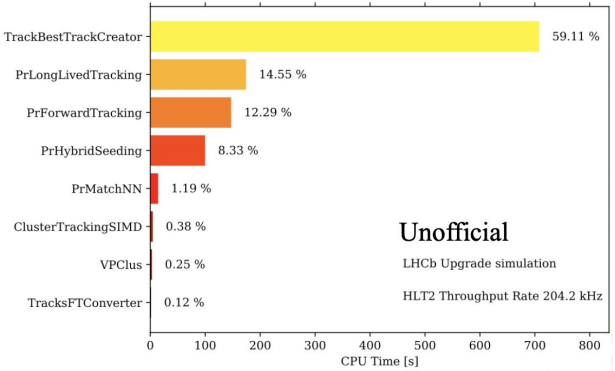
We show **preliminary results** for our quantum algorithm
The tagging power ε_{tag} is the figure of merit for our physics case

- results for classical algorithms are obtained using all the variables and the whole training dataset
- the data re-uploading classifier uses 16 variables, 3200 training events for ~ 100 epochs
- the VQC “a la TN” classifier uses 8 variables, 2000 training events for ~ 100 epochs

- QML performs slightly worse than classical algorithms

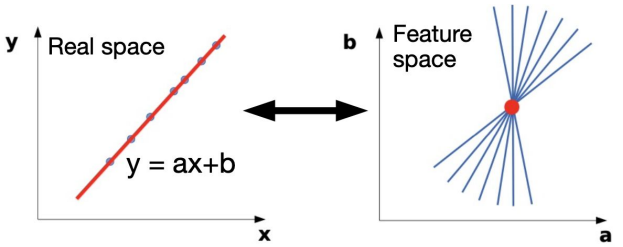
Coming next...pattern recognition!

- The core of LHCb performance is **pattern recognition**
  - Most time consuming aspect in trigger
- Serious problem when increasing luminosity
- How to reconstruct so many particles in real time?



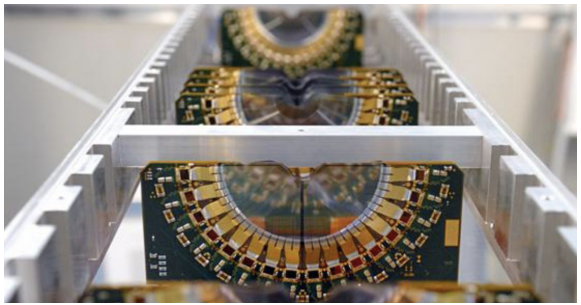
- A possible idea is using **Hough Transform**
  - Algorithm used in image analysis to search for specific shapes in images
  - Search performed in **parameter space**
  - It has been shown that **Quantum Hough Transform** (QHT) has advantages both in computational and space requirements

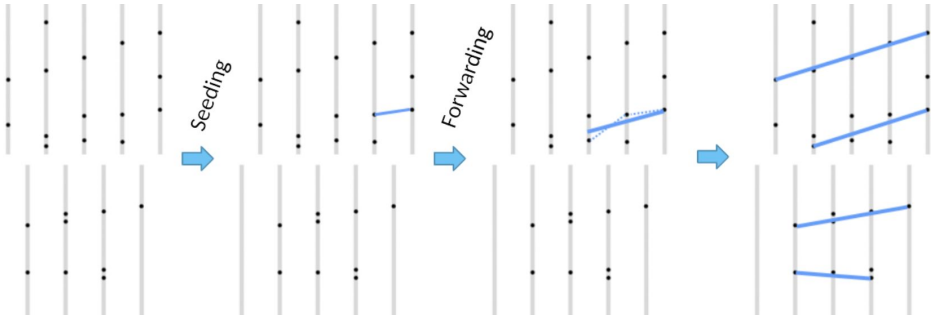
new suggestions are welcome!



Case study @ LHCb for QHT

- A case study has been set up: pattern recognition in VErtex LOcator (VELO)
- 3D space points and straight line tracks
- “triplet search” and “track following” procedure





- Several figures of merit:
  - efficiency
  - ghost rate
- Study started at Maastricht University in collaboration with IBM
  - 2 postdocs (one full-time)
  - initial training @ IBM Zurich

DPA-WP4 @ LHCb

- All these studies are performed and discussed inside the Working Package 4 (WP4) of Data Processing & Analysis Project (DPA) @ LHCb

Work package	Coordinator(s)	Mailing list
Overall coordination	Eduardo Rodrigues	
WP1 - Sprucing	Nicole Skidmore	lhcb-dpa-wp1
WP2 - Analysis Productions	Chris Burr	lhcb-dpa-wp2
WP3 - Offline Analysis Tools	Patrick Koppenburg	lhcb-dpa-wp3
WP4 - Innovative Analysis Techniques	Donatella Lucchesi	lhcb-dpa-wp4
WP5 - Legacy Software & Data	Alison Tully	lhcb-dpa-wp5
WP6 - Analysis Preservation & Open Data	Sebastian Neubert	lhcb-data-preservation

WP4 - Innovative Analysis Techniques

The activities of this group aim at discussing new software and hardware technologies, finding possible LHCb applications and test them within the LHCb software environment. If the tests are successful, we will work to include the developed code in the LHCb mainstream.

- Think tank for new ideas and proofs of concept to be tested and afterwards applied to LHCb analysis
- **New studies and results are on their way**

COMING SOON!

Final remarks

- **quantum applications** for HEP problems are ongoing @ LHCb

- first “proof of concept” of QML for jet tagging @LHCb
  - we use the **official LHCb simulation**, resembling real LHCb data
  - algorithms run on **noiseless simulator** and results are **very promising**

- **pattern recognition** @LHCb would be an open problem
  - mandatory **speed up** to process a lot of particles in real time
  - this is where “**quantum**” could play an interesting role (QHT, …)

STARTING SOON!

- **increasing interest** @ LHCb DPA-WP4 for new quantum applications

Thank you for your attention

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