Reconstructing charged particle track segments with a quantum-enhanced support vector machine

P. Duckett, G. Facini, M. Jastrzebski, S. Malik, S. Rettie, T. Scanlon

https://arxiv.org/abs/2212.07279

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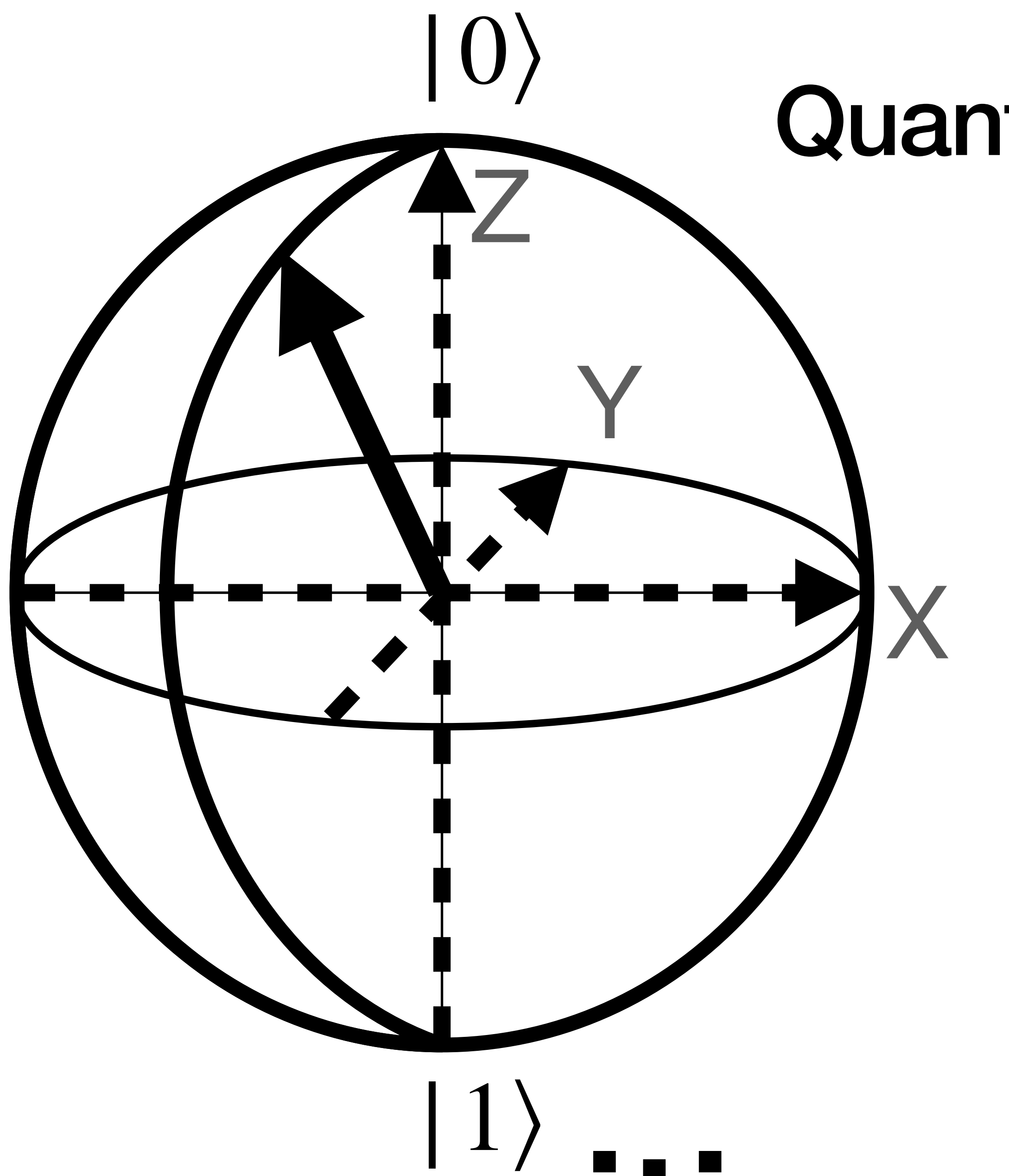
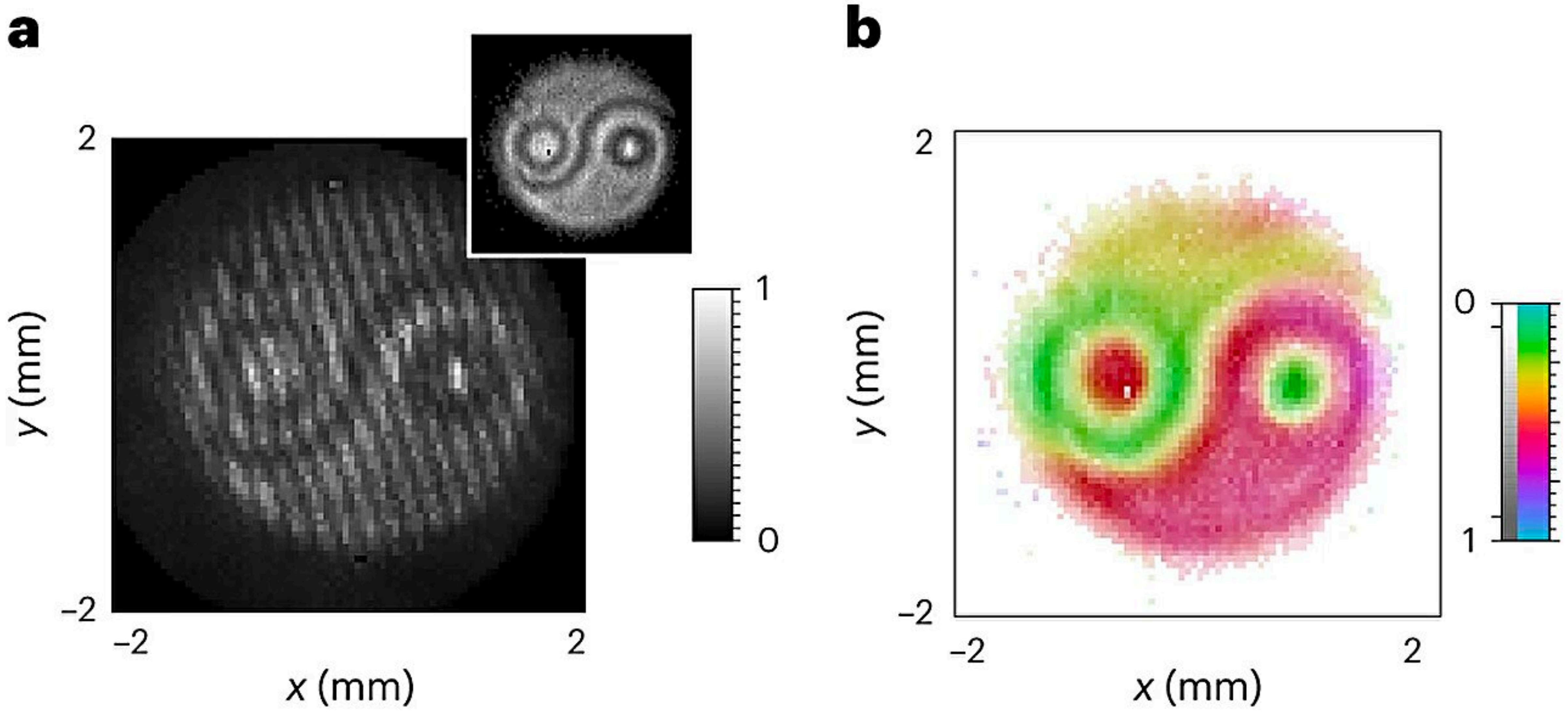
Quantum computation

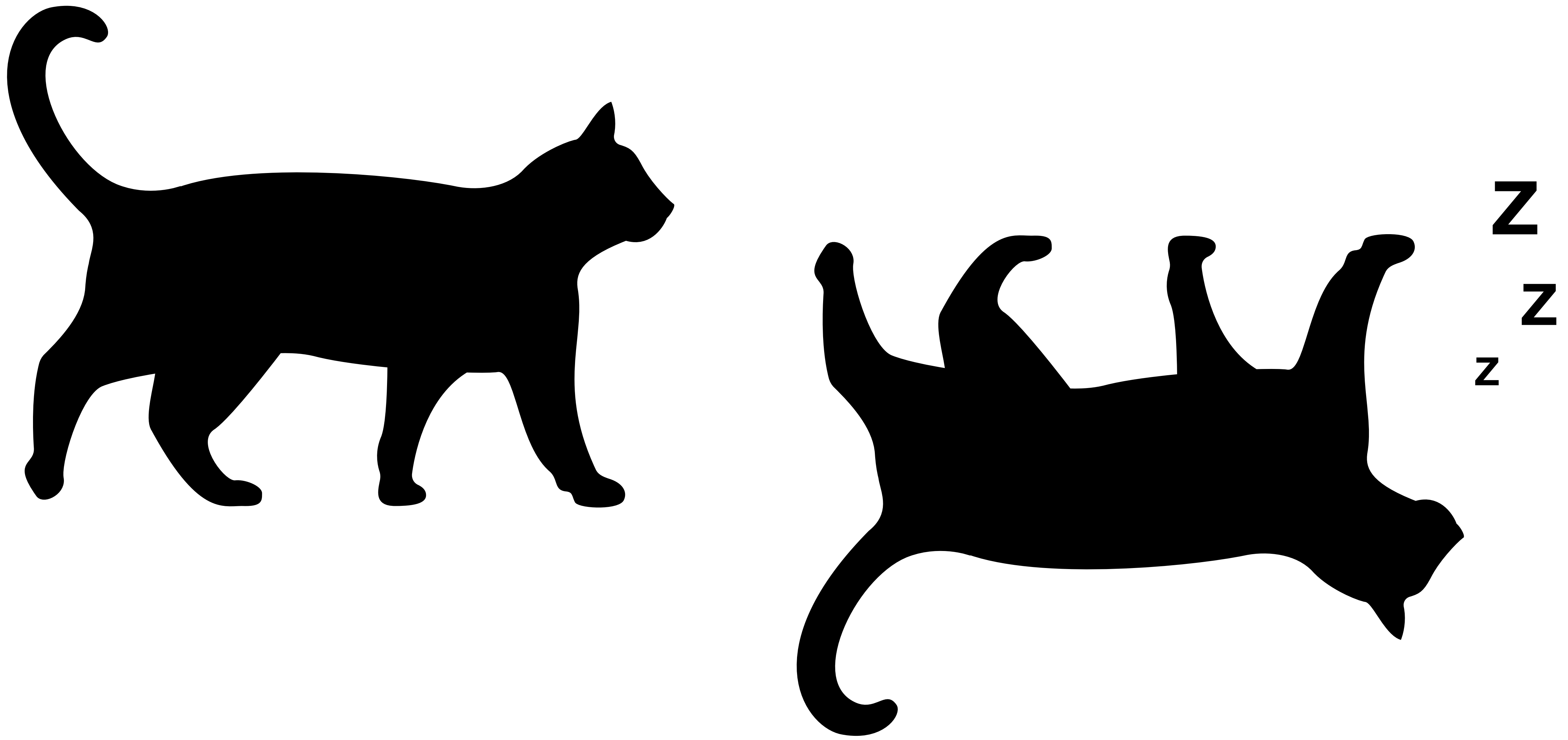


Quantum bit (qubit)

Superposition



Entanglement

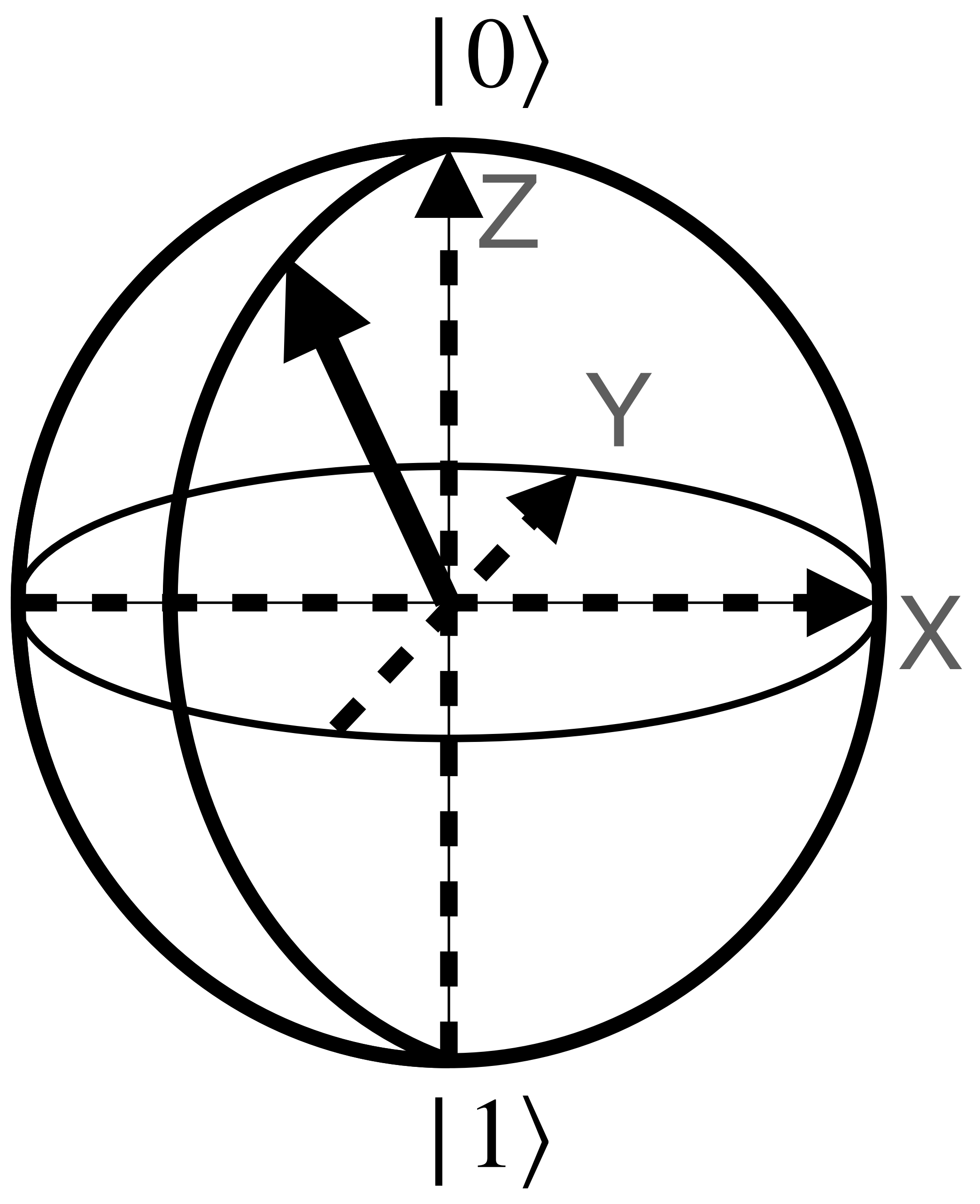


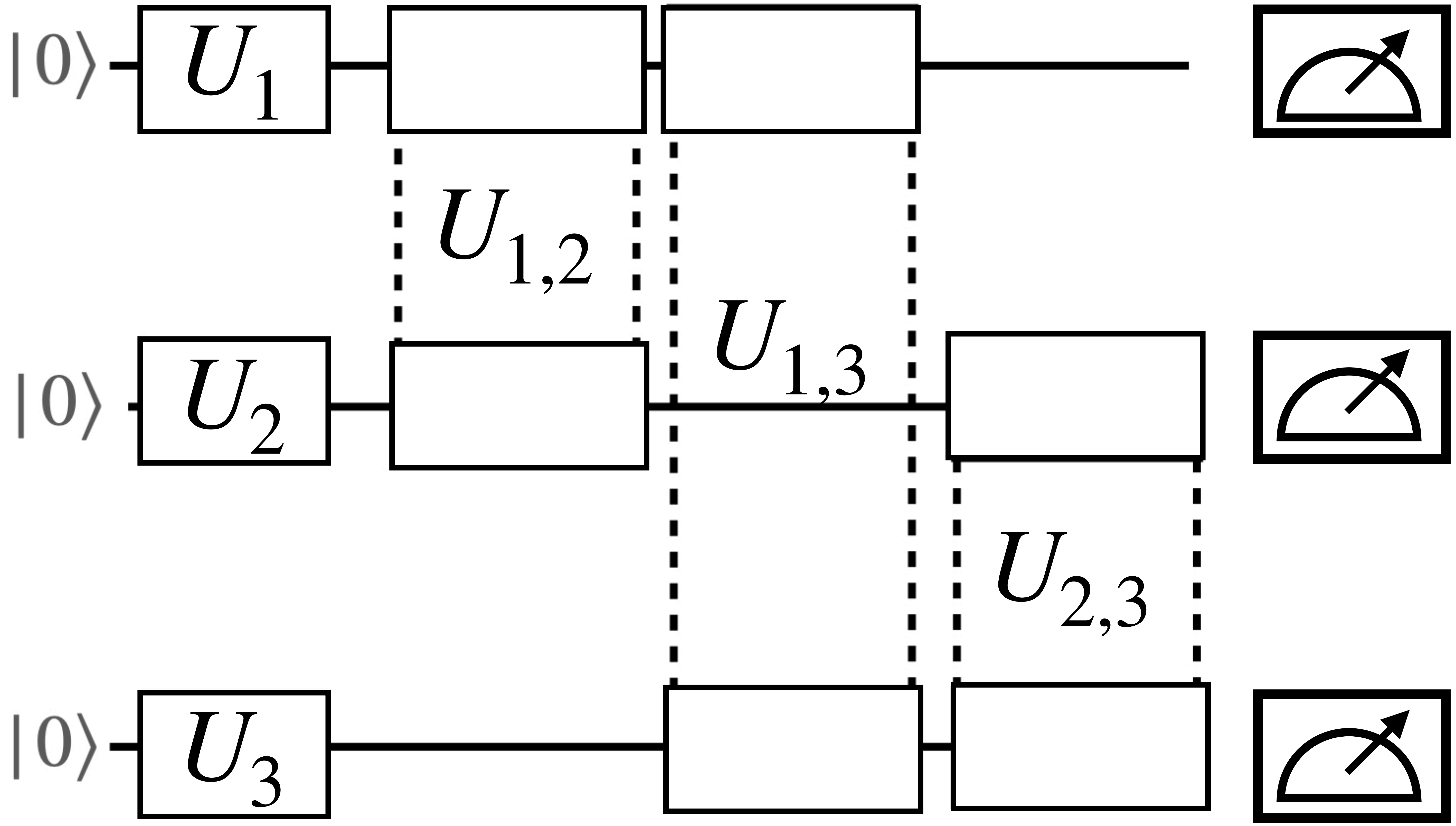
Randomness

Quantum computation - circuit

$$|0\rangle^{\otimes N} \longrightarrow (\alpha|0\rangle + \beta|1\rangle)^{\otimes N} \longrightarrow \alpha|00\ldots0\rangle + \beta|00\ldots1\rangle + \ldots \longrightarrow (011\ldots1)$$

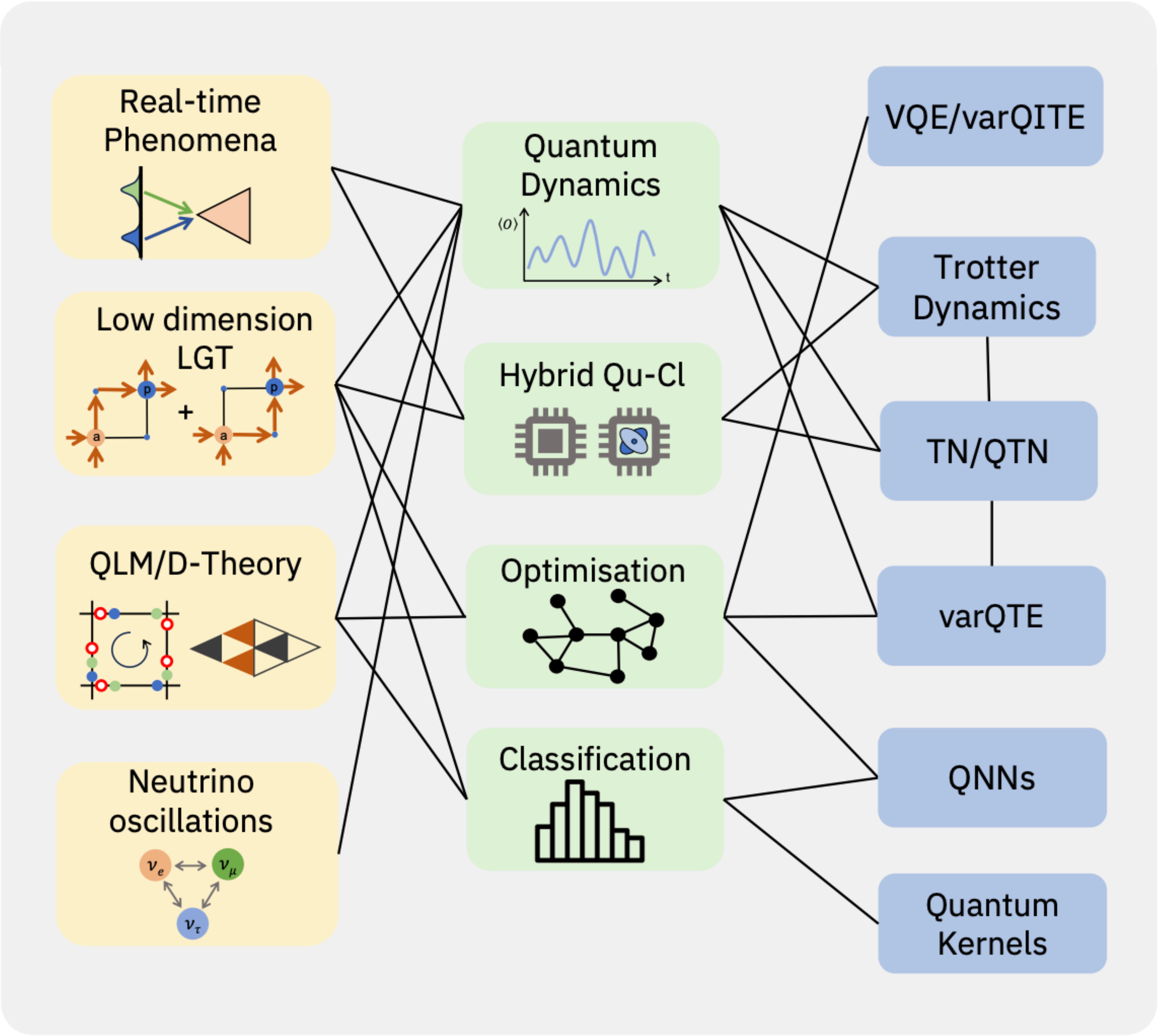
Superposition   Entanglement   Randomness



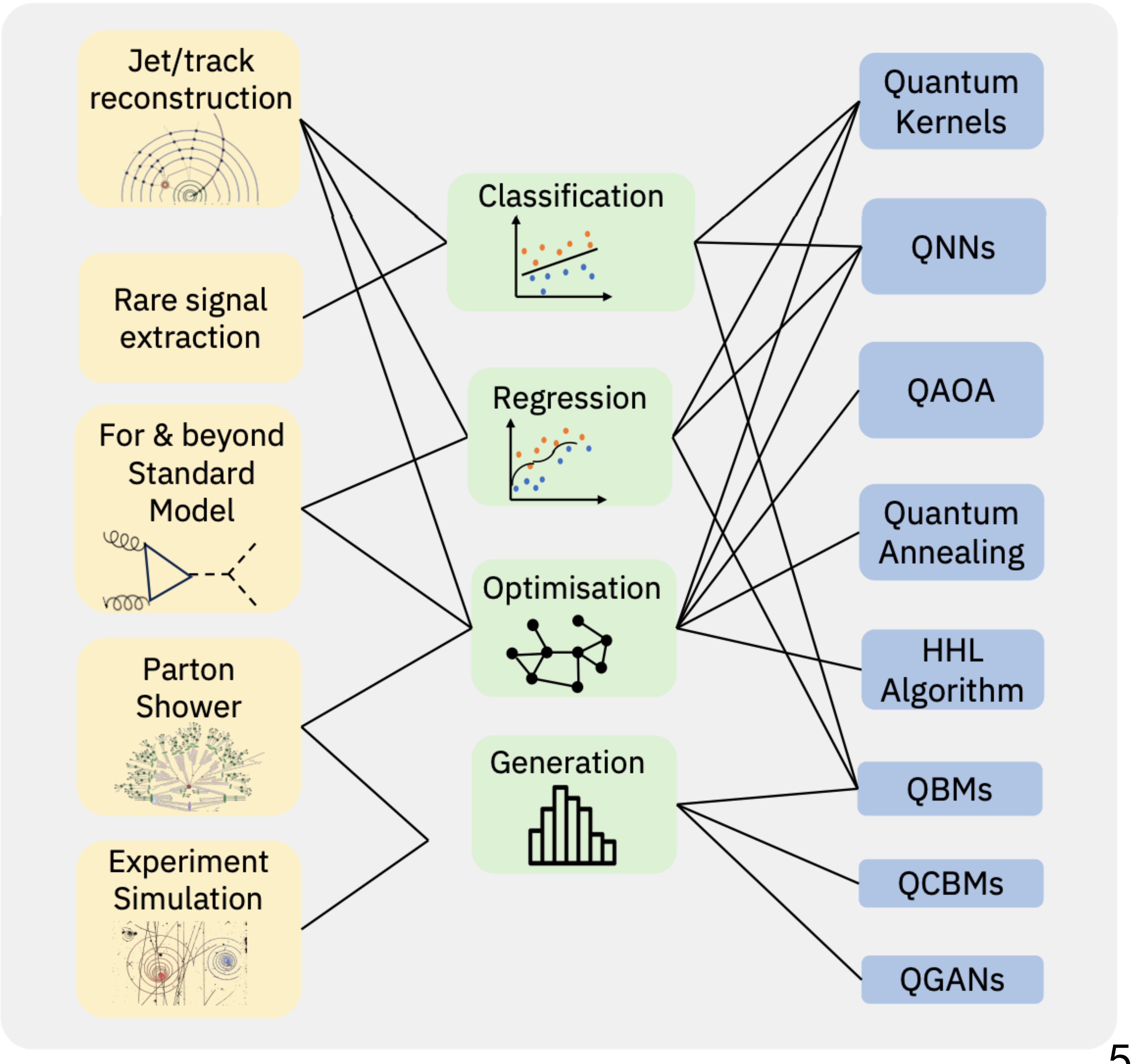


QC for HEP landscape

Theory

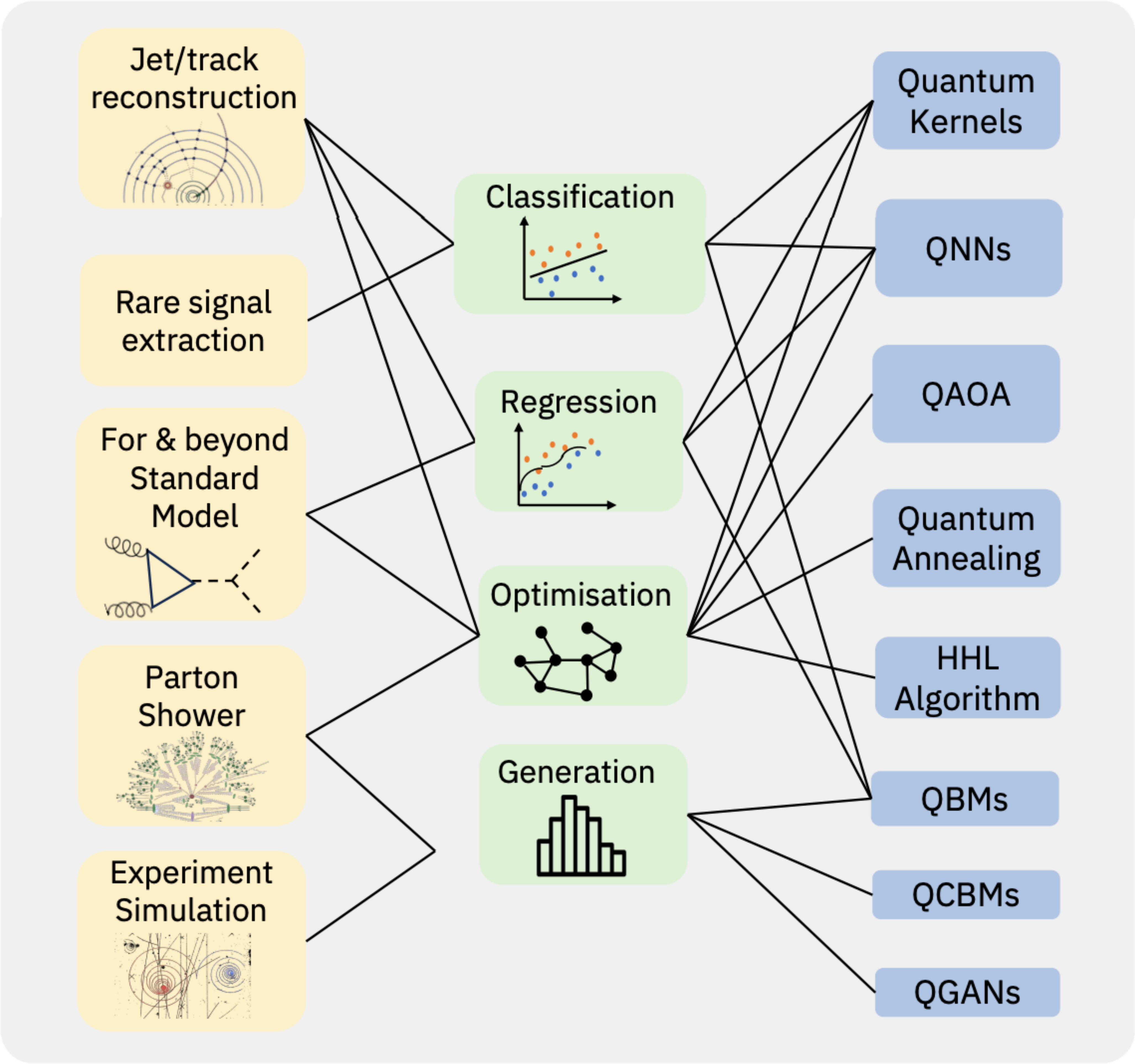


Experiment



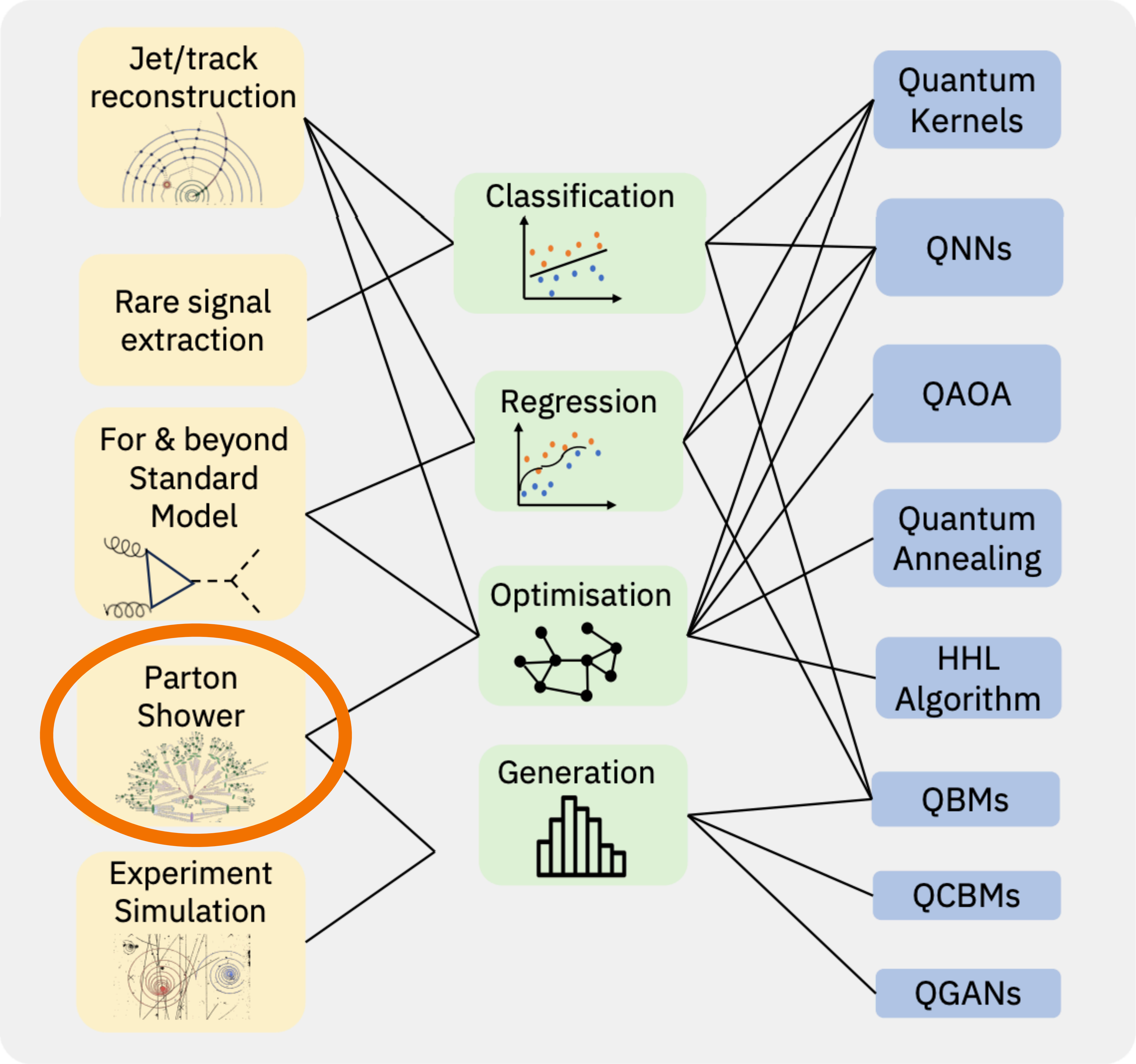
QC for HEP landscape

Experiment



QC for HEP landscape

Experiment



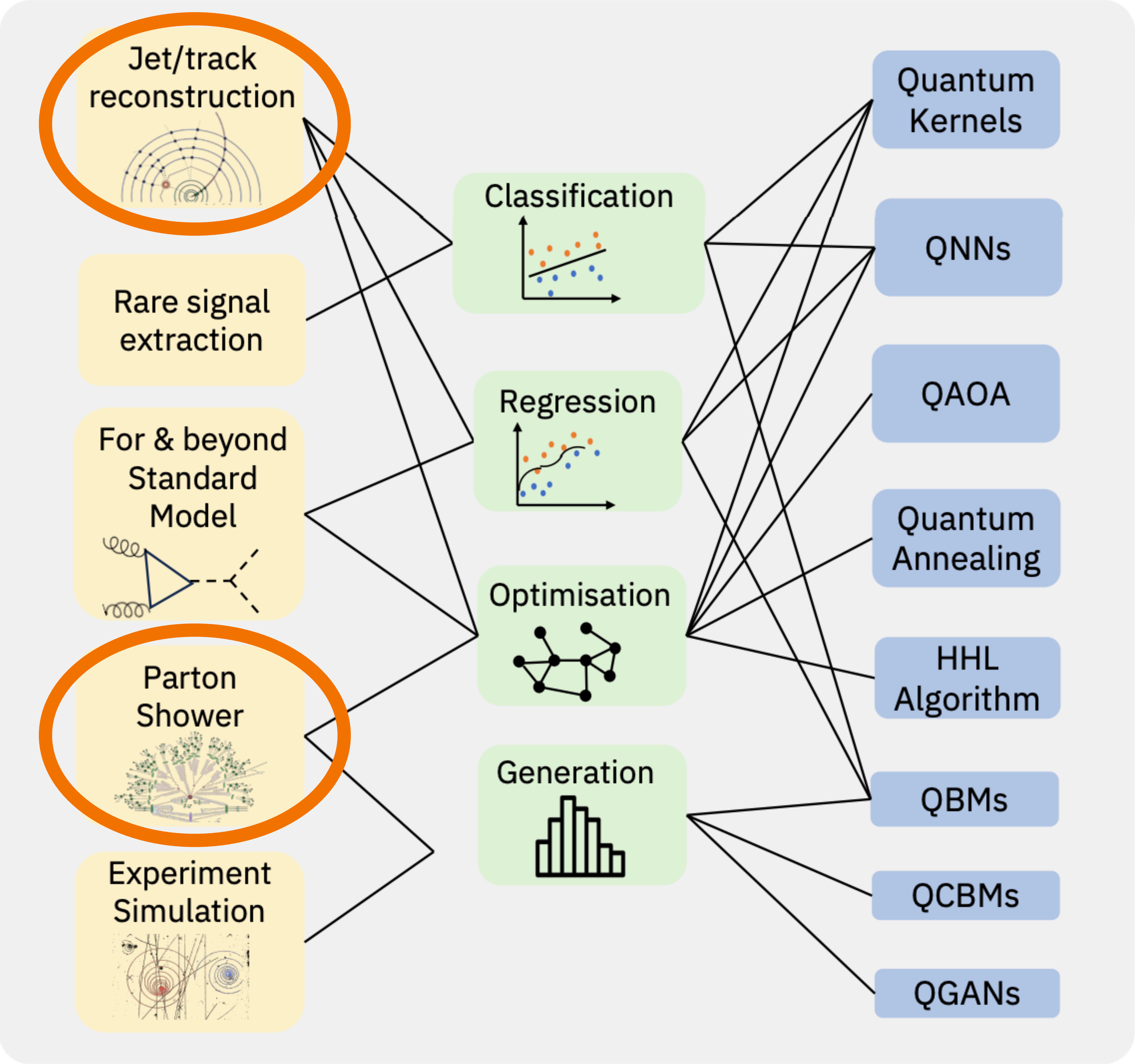
Check out

https://www.nature.com/articles/s42254-022-00528-1

QC for HEP landscape

Experiment

This workshop



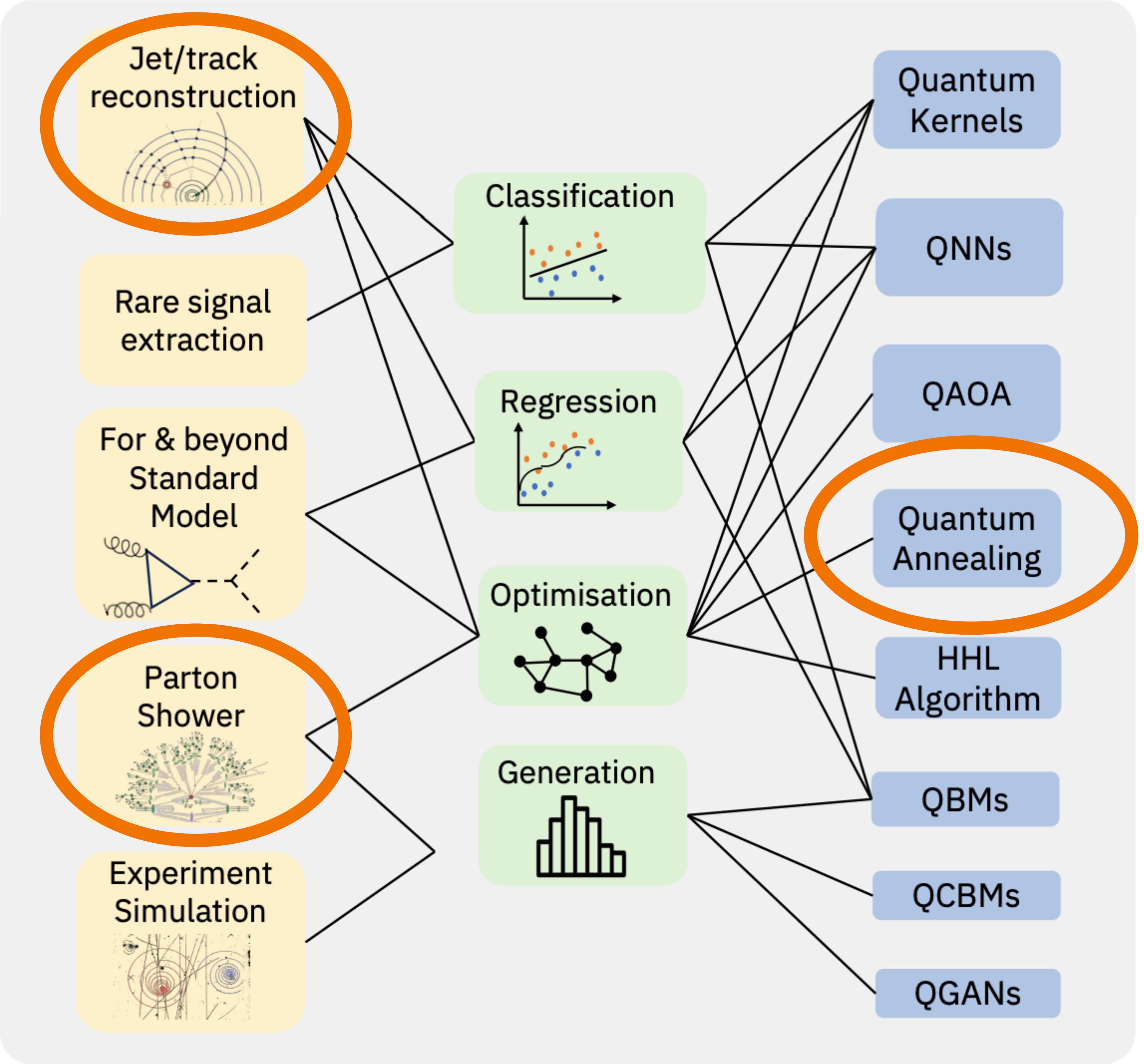
Check out

https://www.nature.com/articles/s42254-022-00528-1

QC for HEP landscape

Experiment

This workshop



Later today

Check out

https://www.nature.com/articles/s42254-022-00528-1

QC for HEP landscape

Experiment

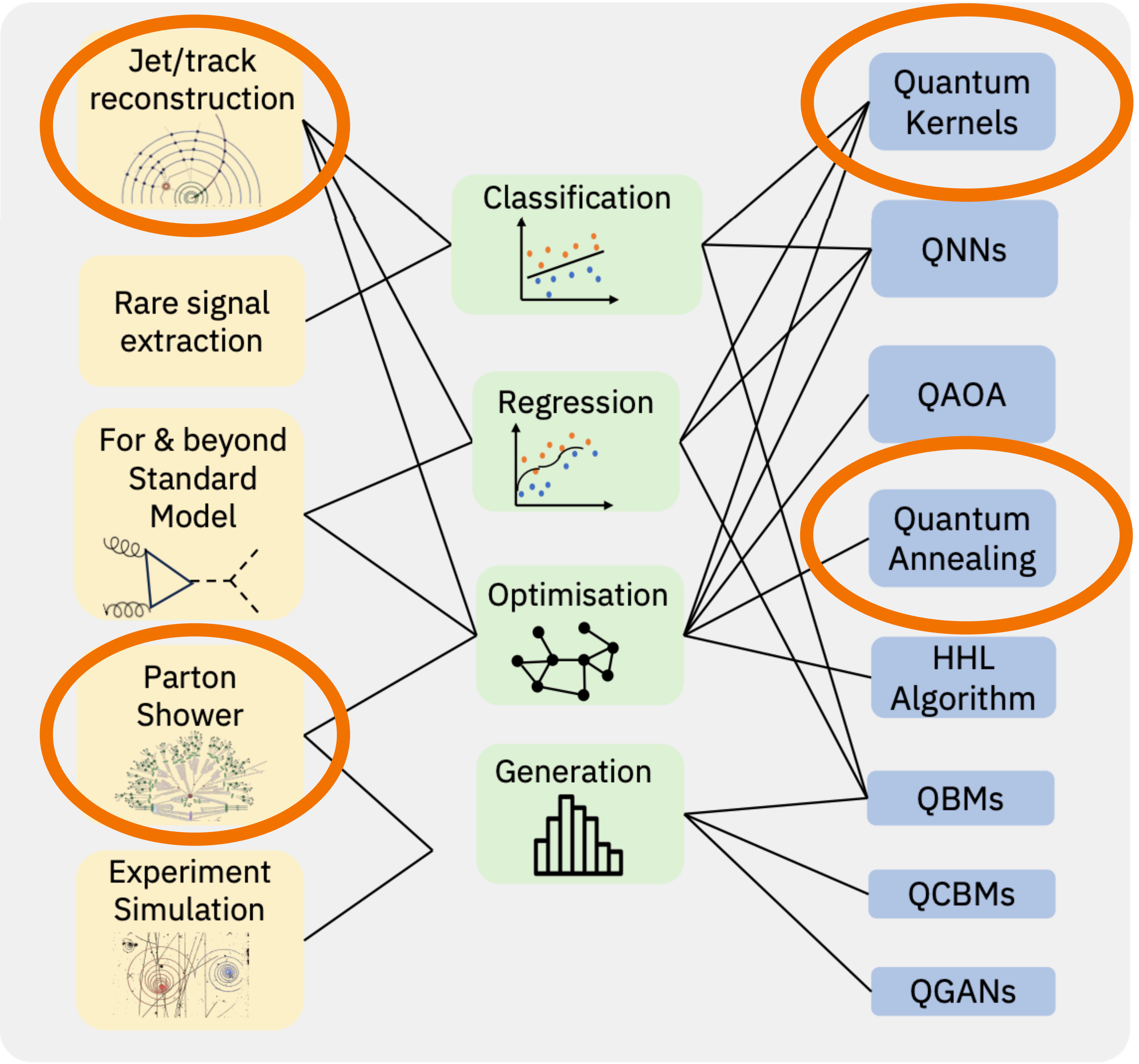
This workshop

Right now!

Later today

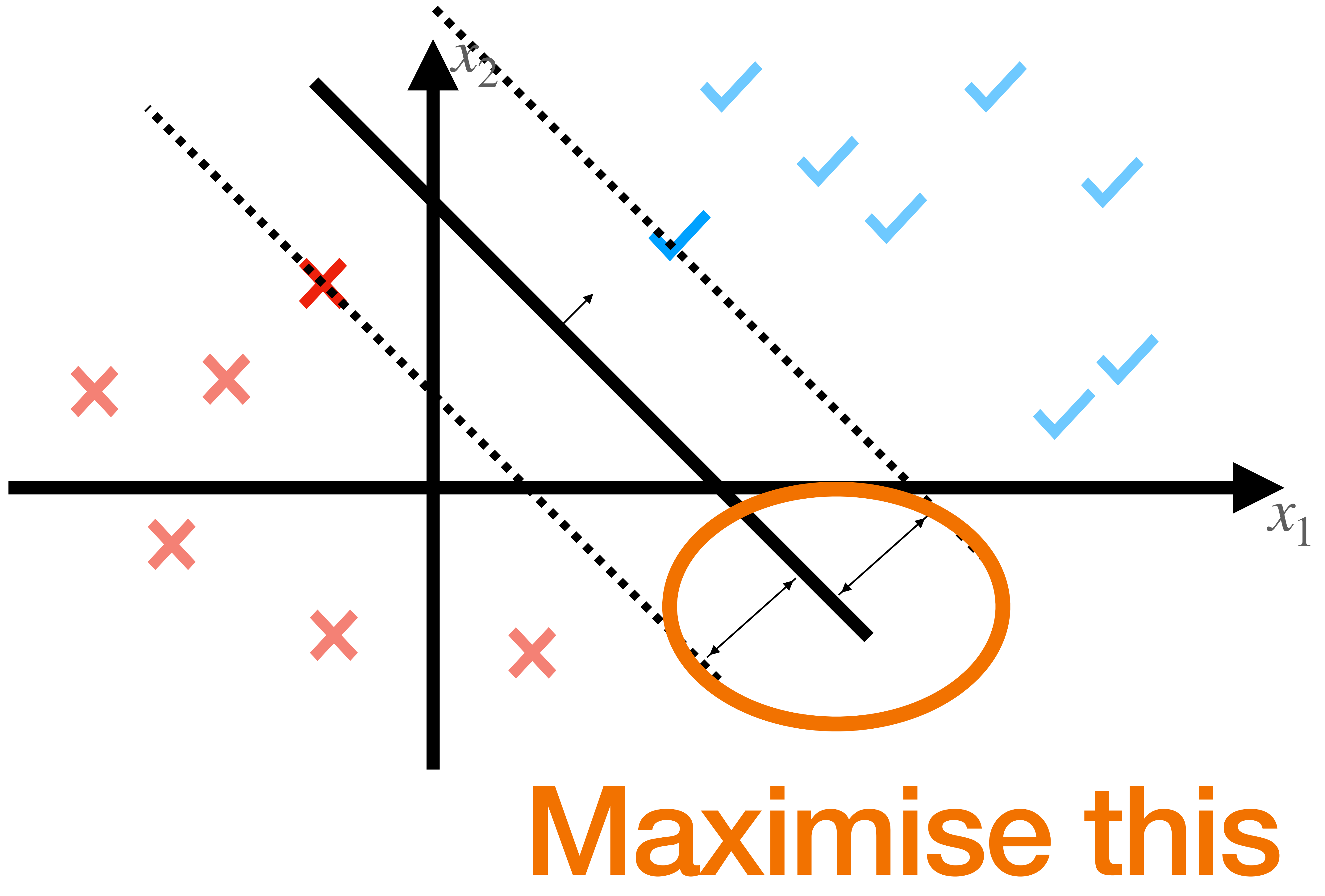
Check out

https://www.nature.com/articles/s42254-022-00528-1



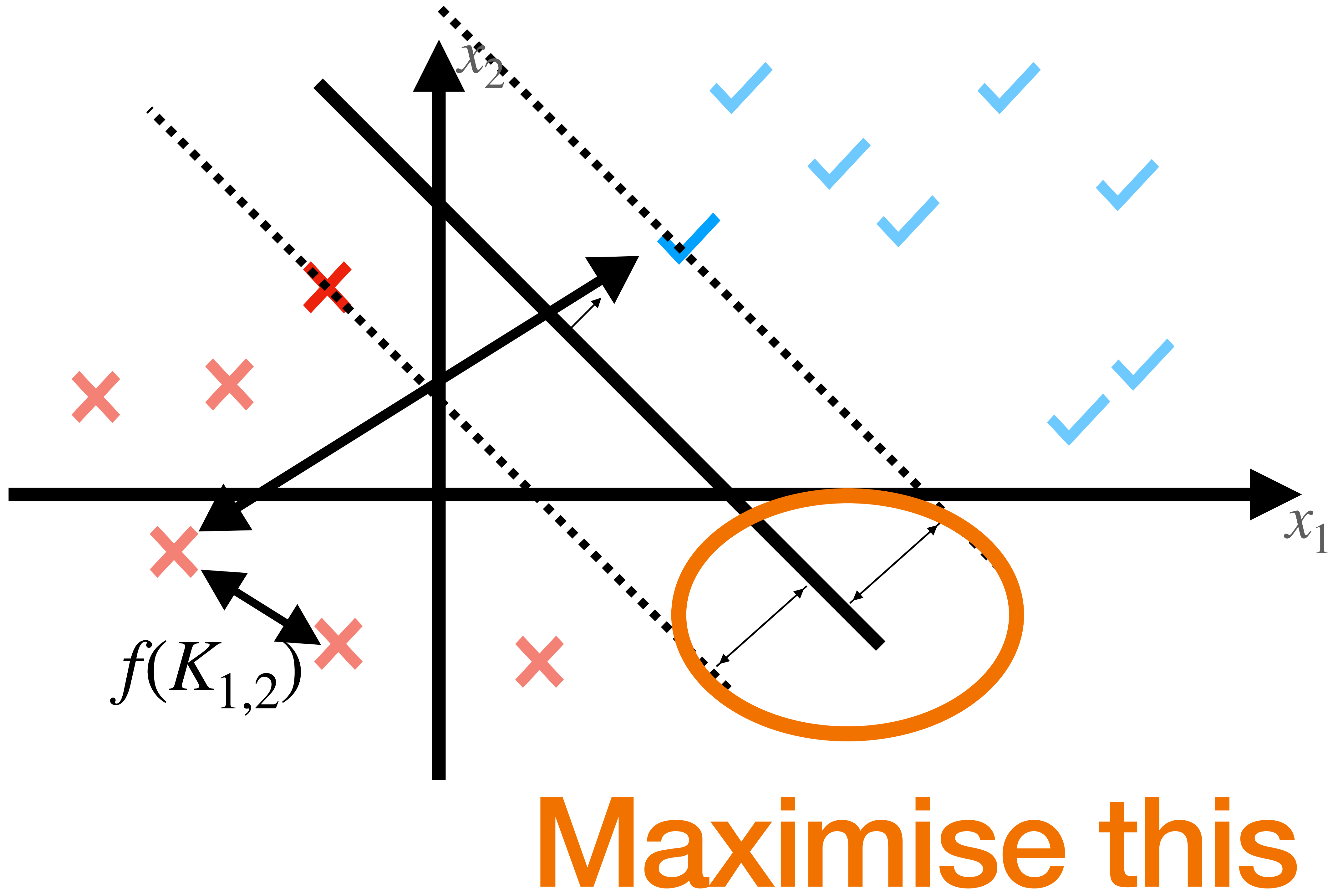
Intro to SVM

Usually done using the dual (think Lagrangian multipliers)



Intro to SVM

Usually done using the dual (think Lagrangian multipliers)

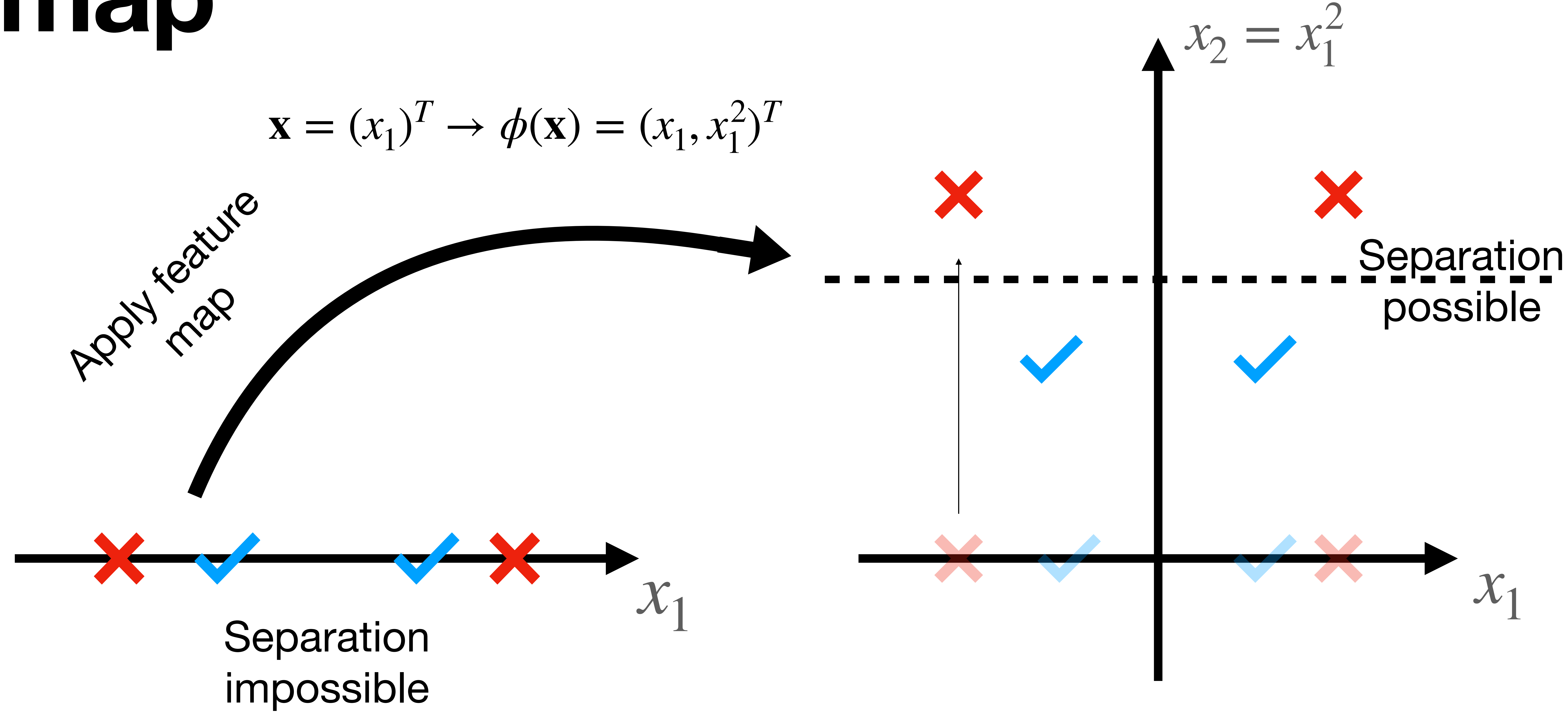


Results in building a kernel matrix

$K_{1,1}$	$K_{1,2}$	$K_{1,3}$
$K_{2,1}$	$\ddots$	

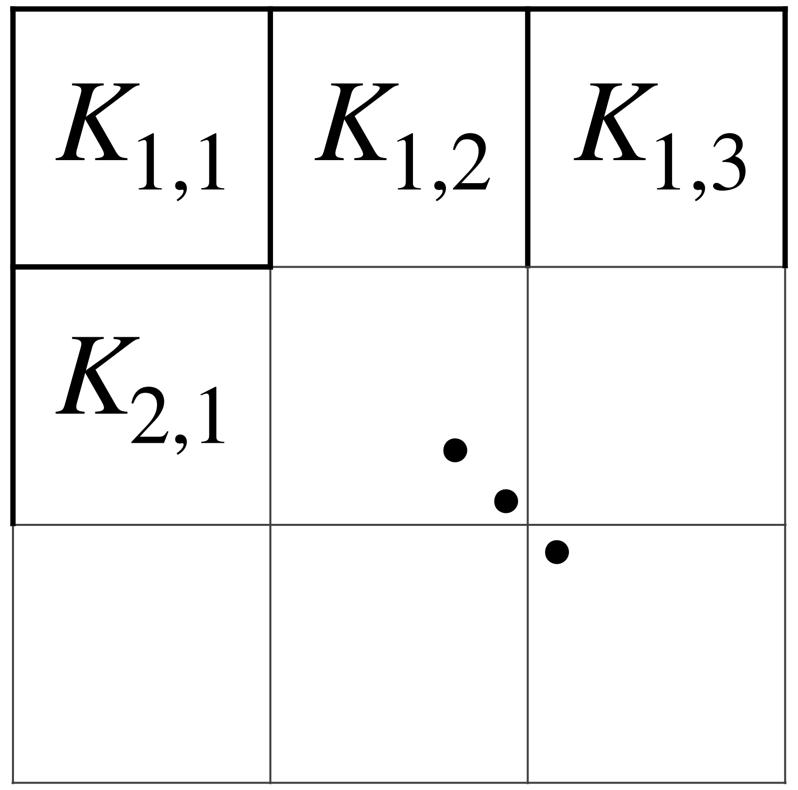
Intro to SVM - feature map

$$\mathbf{x} = (x_1)^T \rightarrow \phi(\mathbf{x}) = (x_1, x_1^2)^T$$

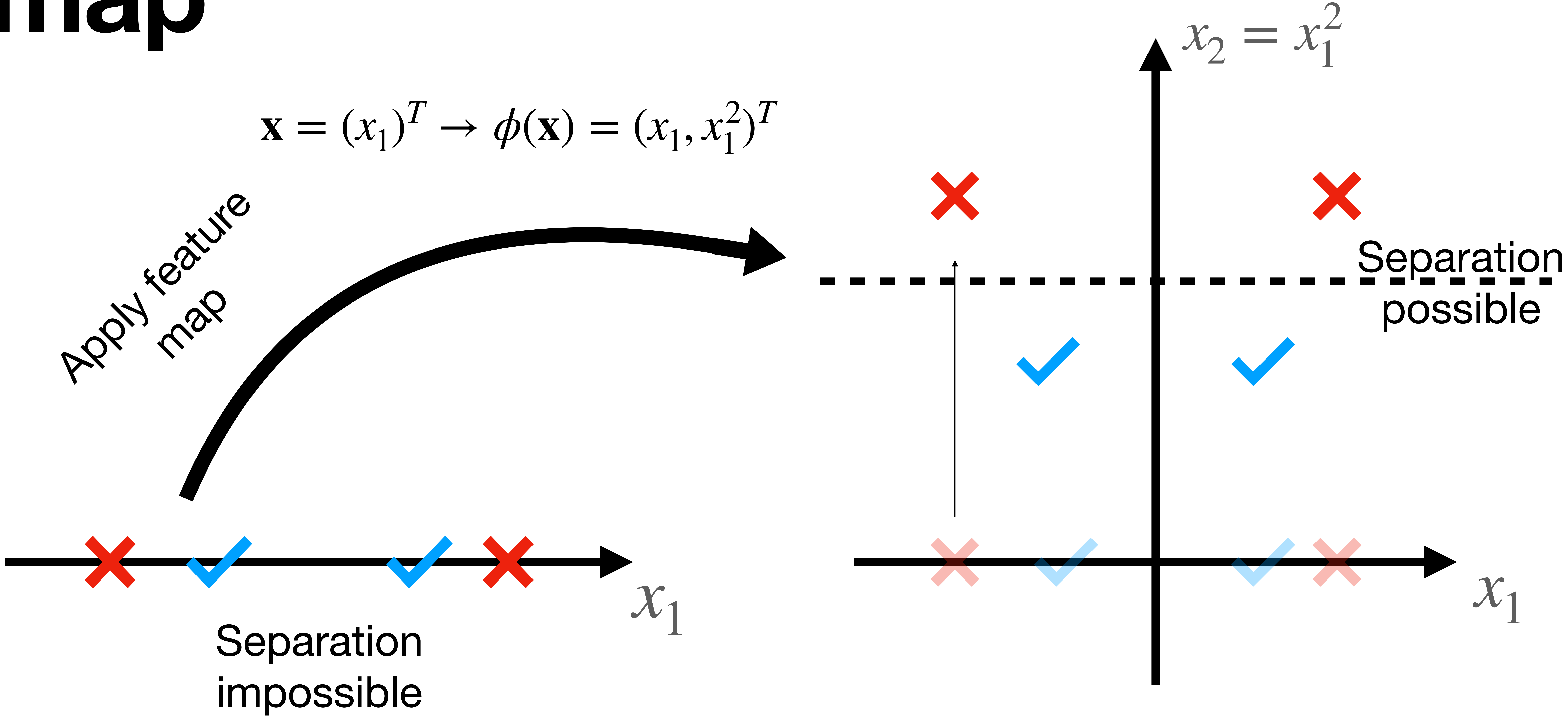


Intro to SVM - feature map

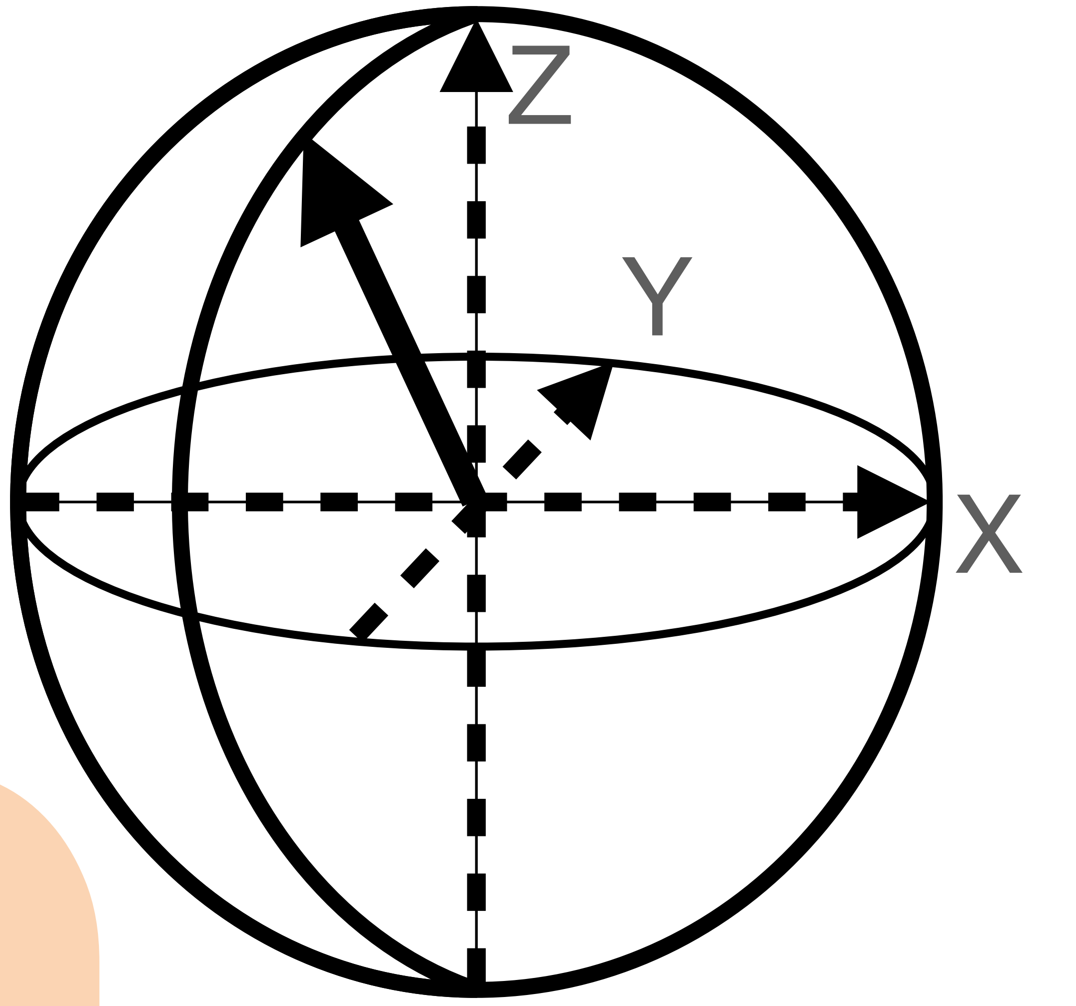
Feature map hidden in

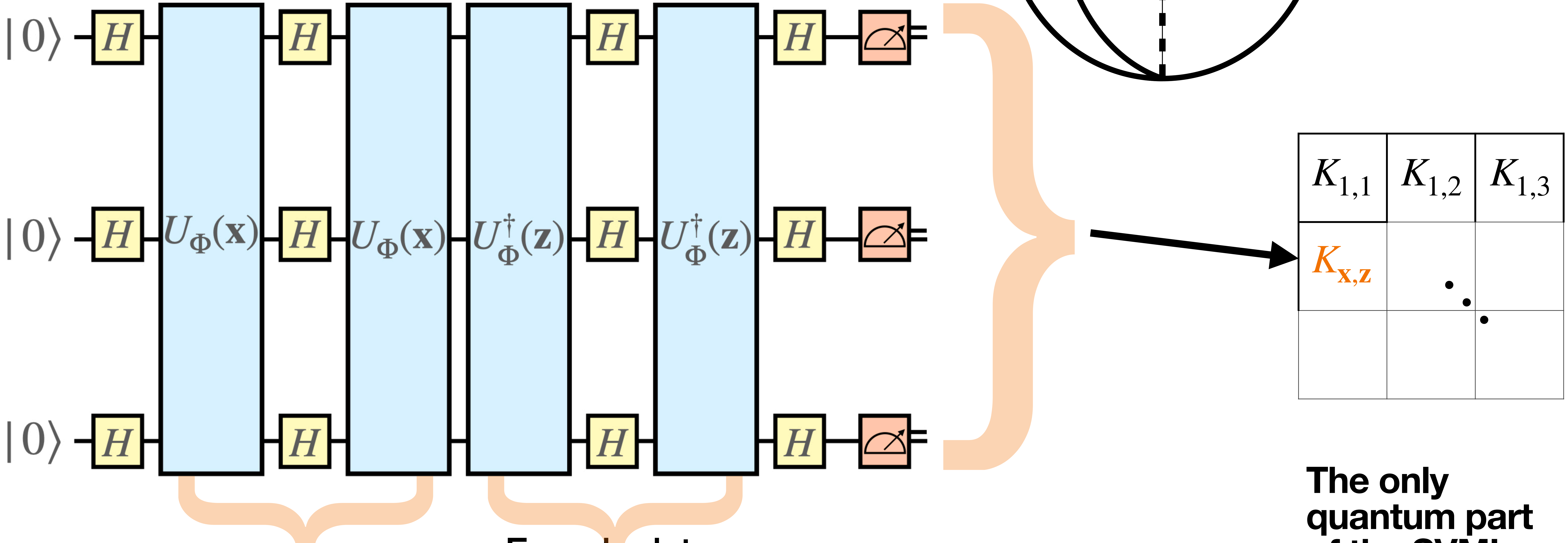


$$\mathbf{x} = (x_1)^T \rightarrow \phi(\mathbf{x}) = (x_1, x_1^2)^T$$



Quantum circuit as feature map and kernel

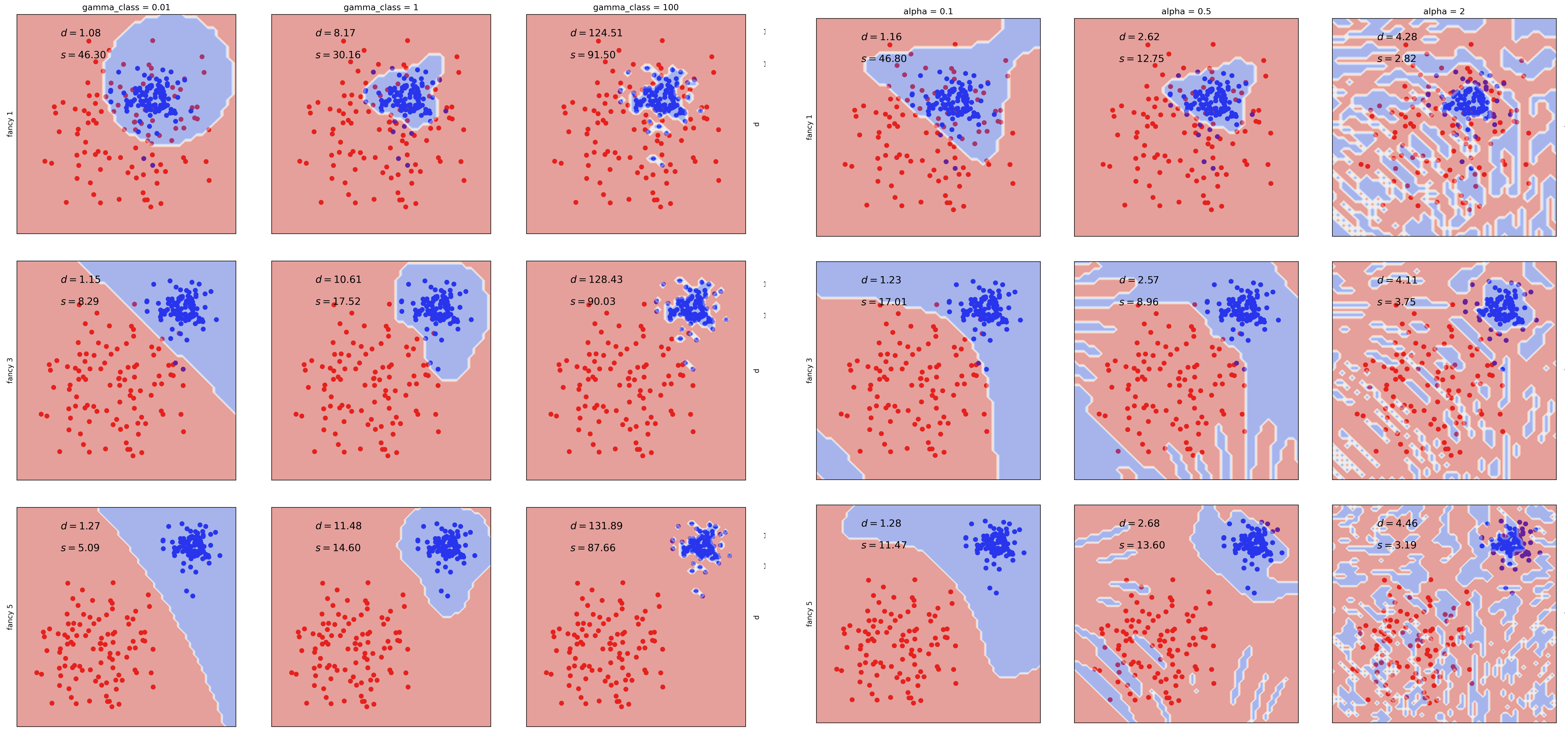




Encode data point **x** in the circuit

Encode data point **z** in the circuit (backwards)

The only quantum part of the SVM!

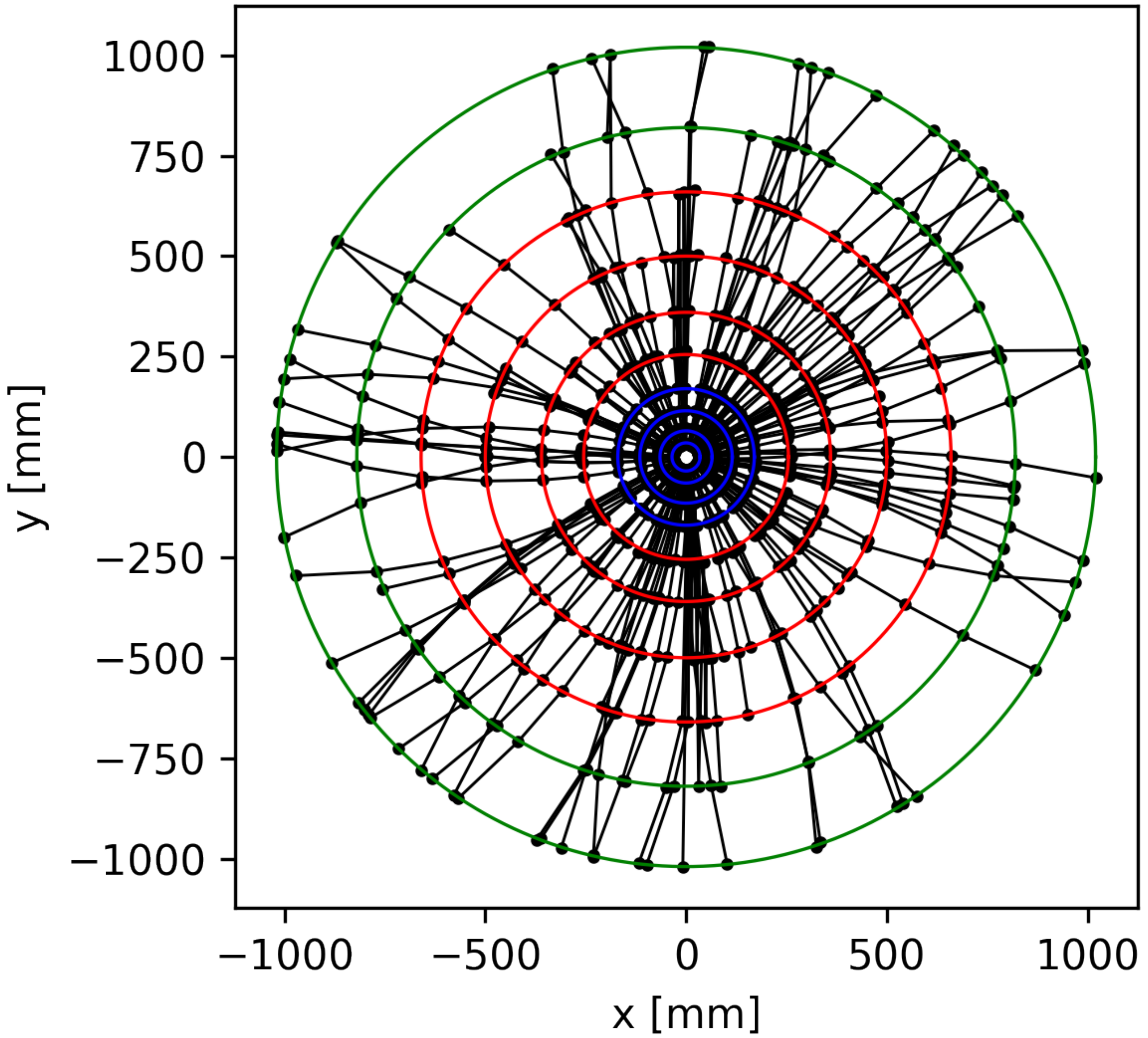


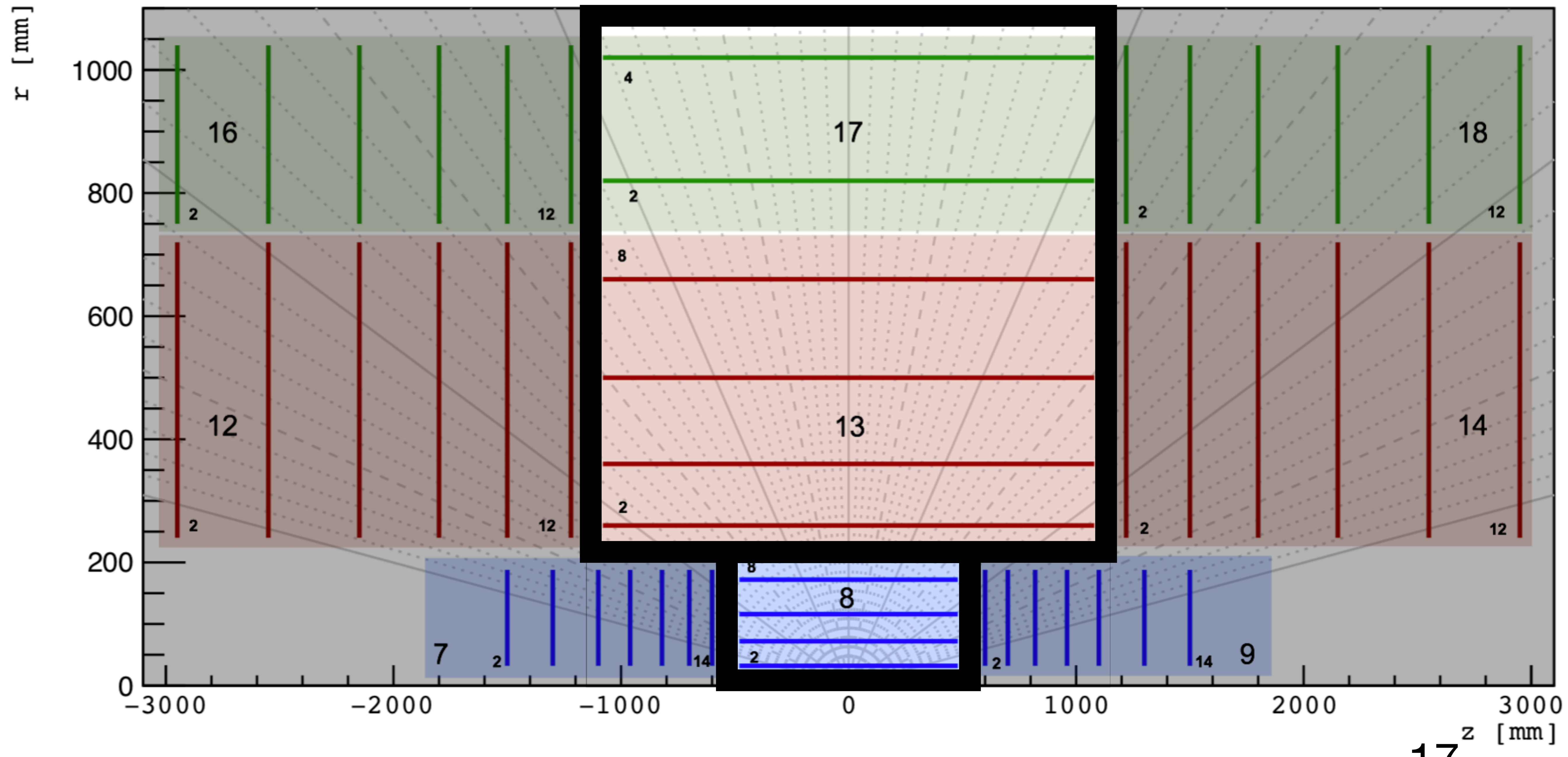
Classical **Quantum**

Dataset + Simplifications

kaggle

- Barrel only
- Remove noise
- One hit per track per layer
- Look at >0.75GeV only

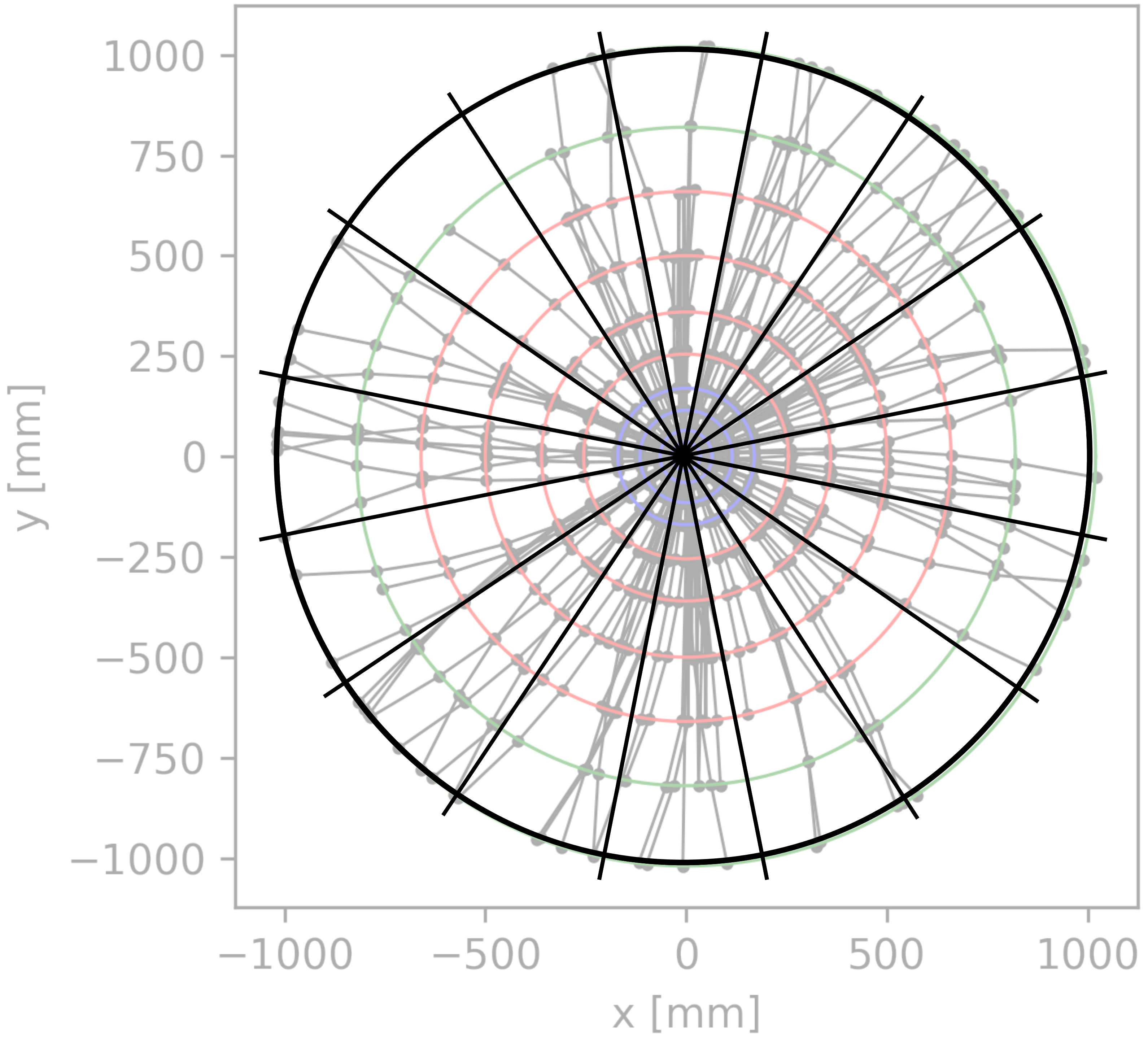


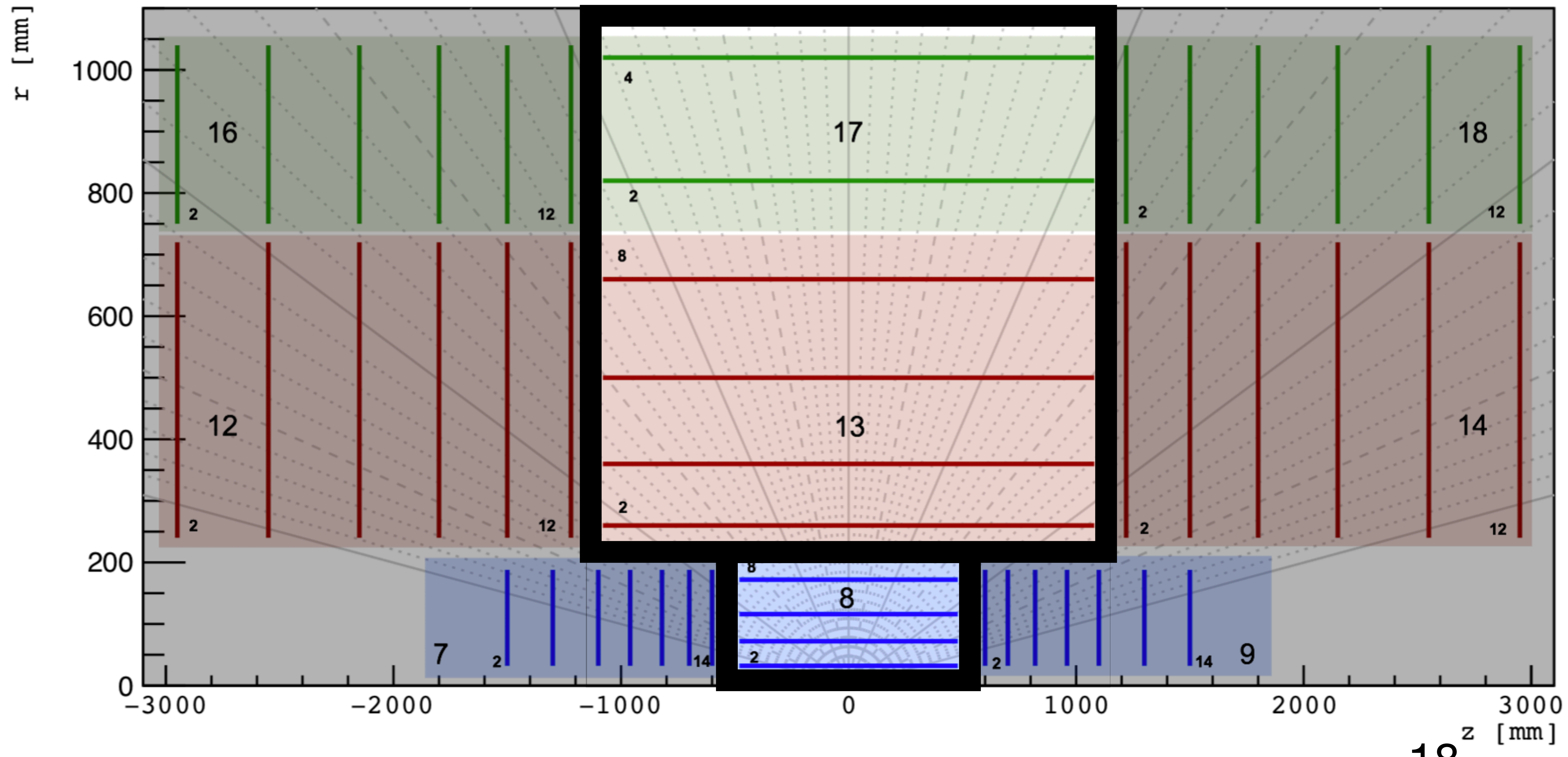


Dataset
+
Simplifications

kaggle

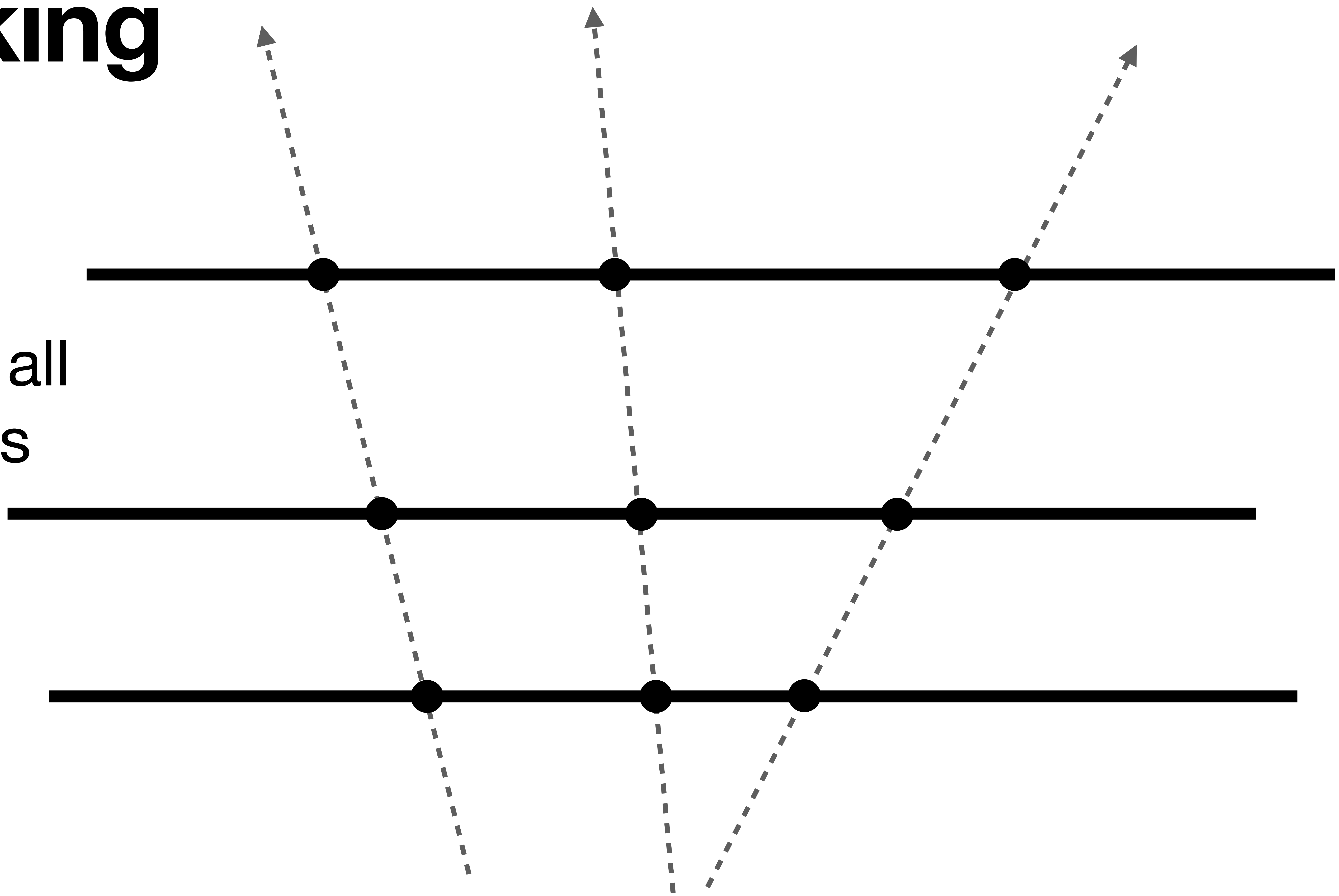
- Slice-up the detector





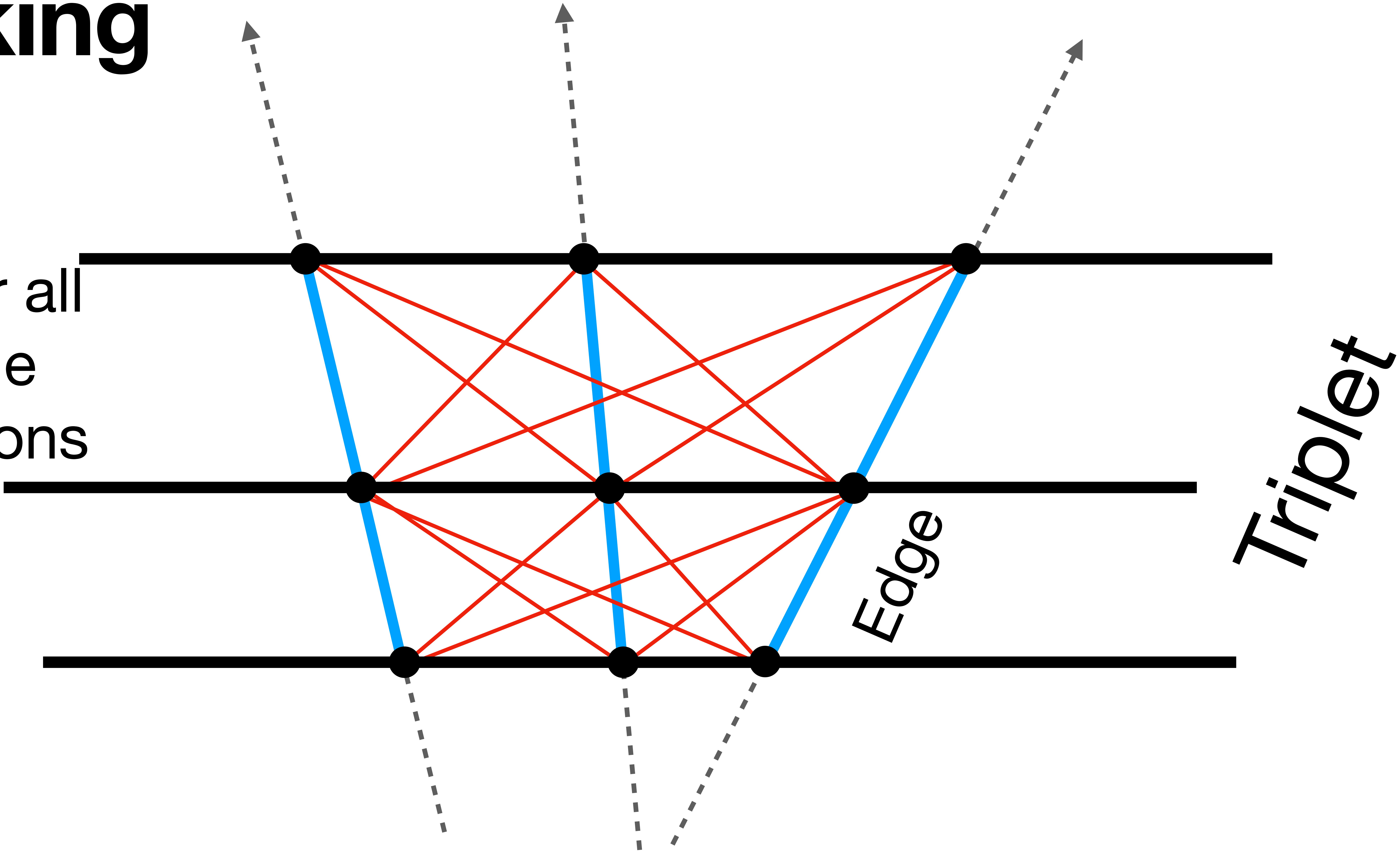
Recap of tracking

Record all the hits



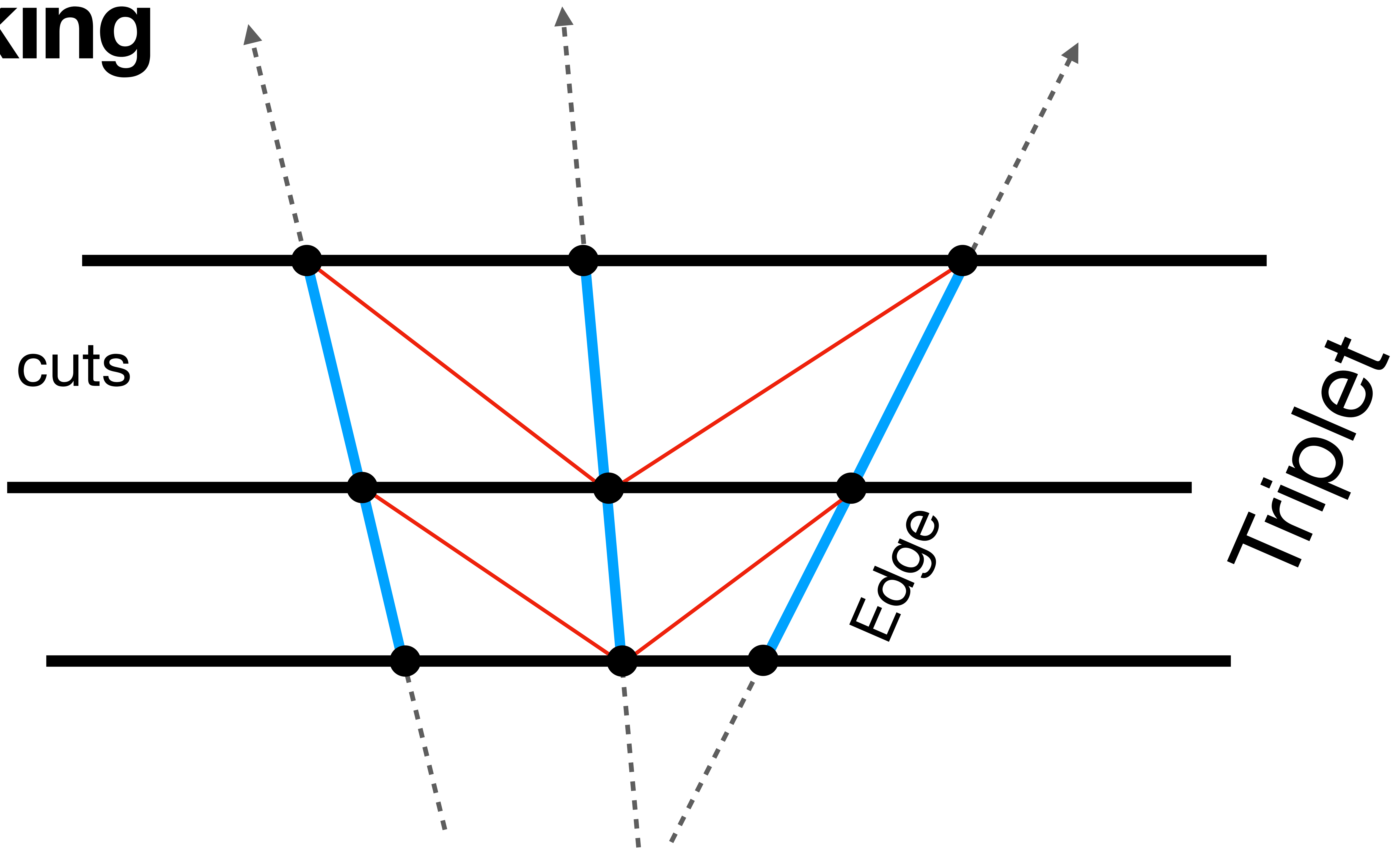
Recap of tracking

Consider all possible connections



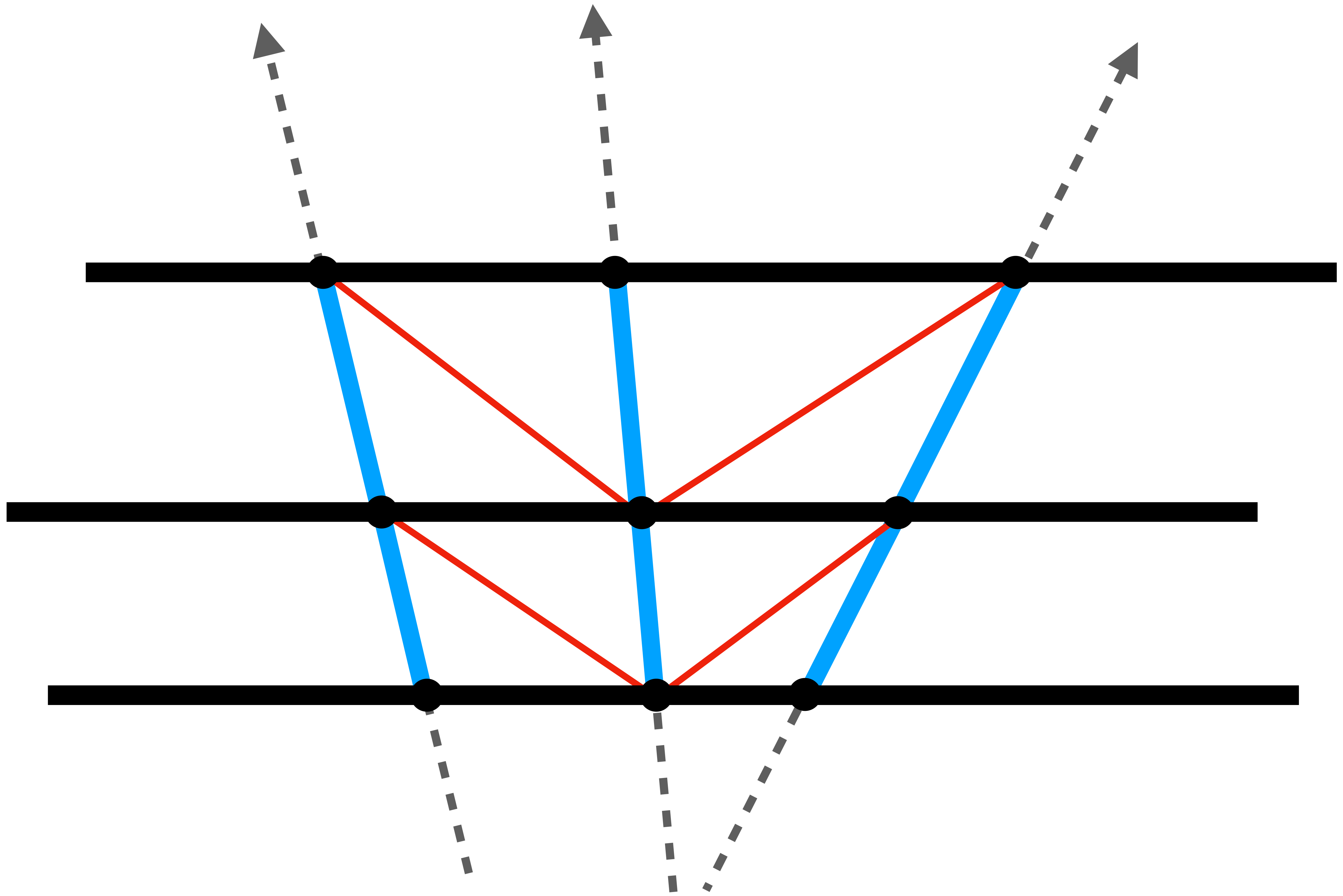
Recap of tracking

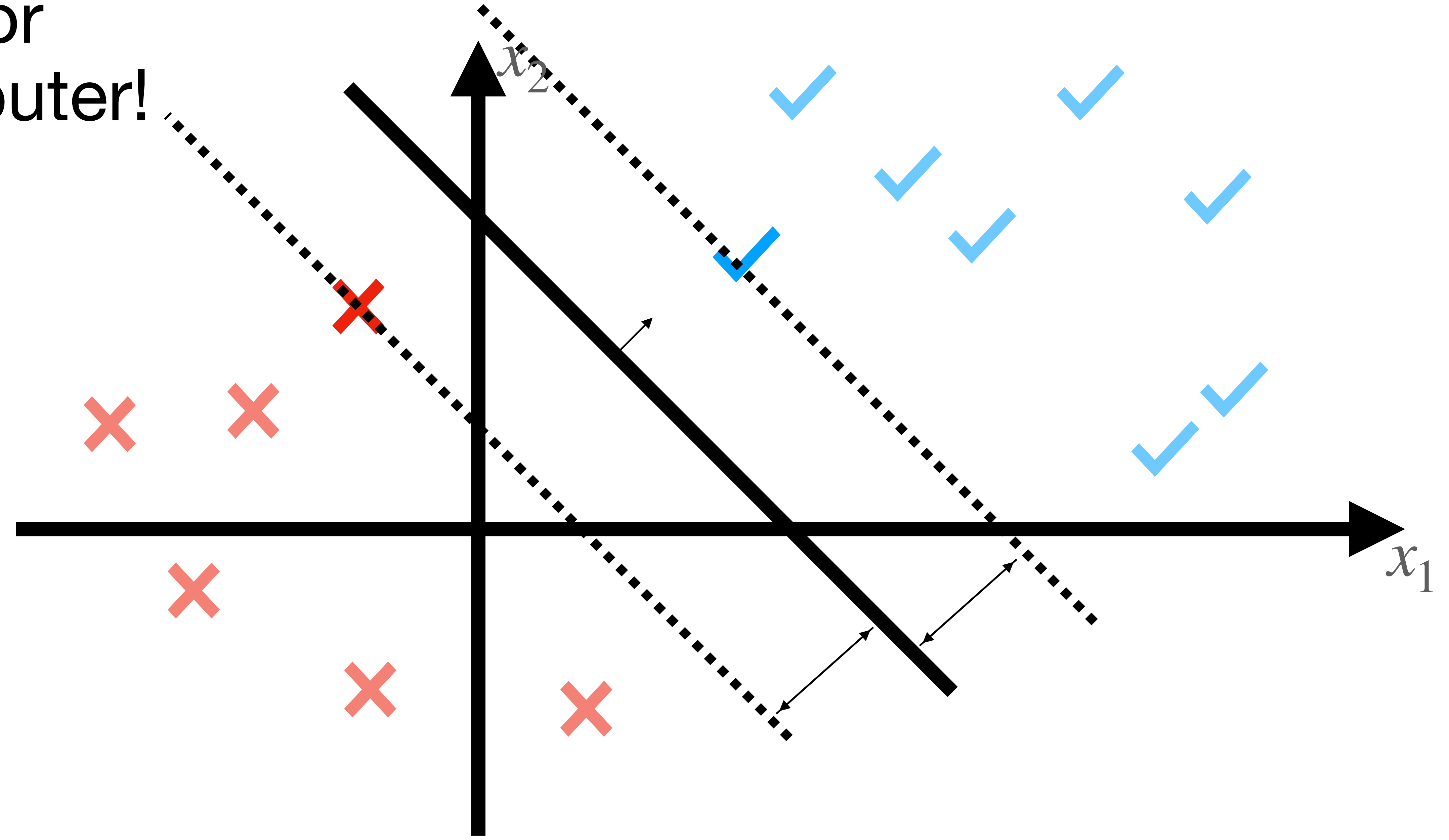
Apply cuts



Intro to SVM

Kernel for this with a classical or quantum computer!

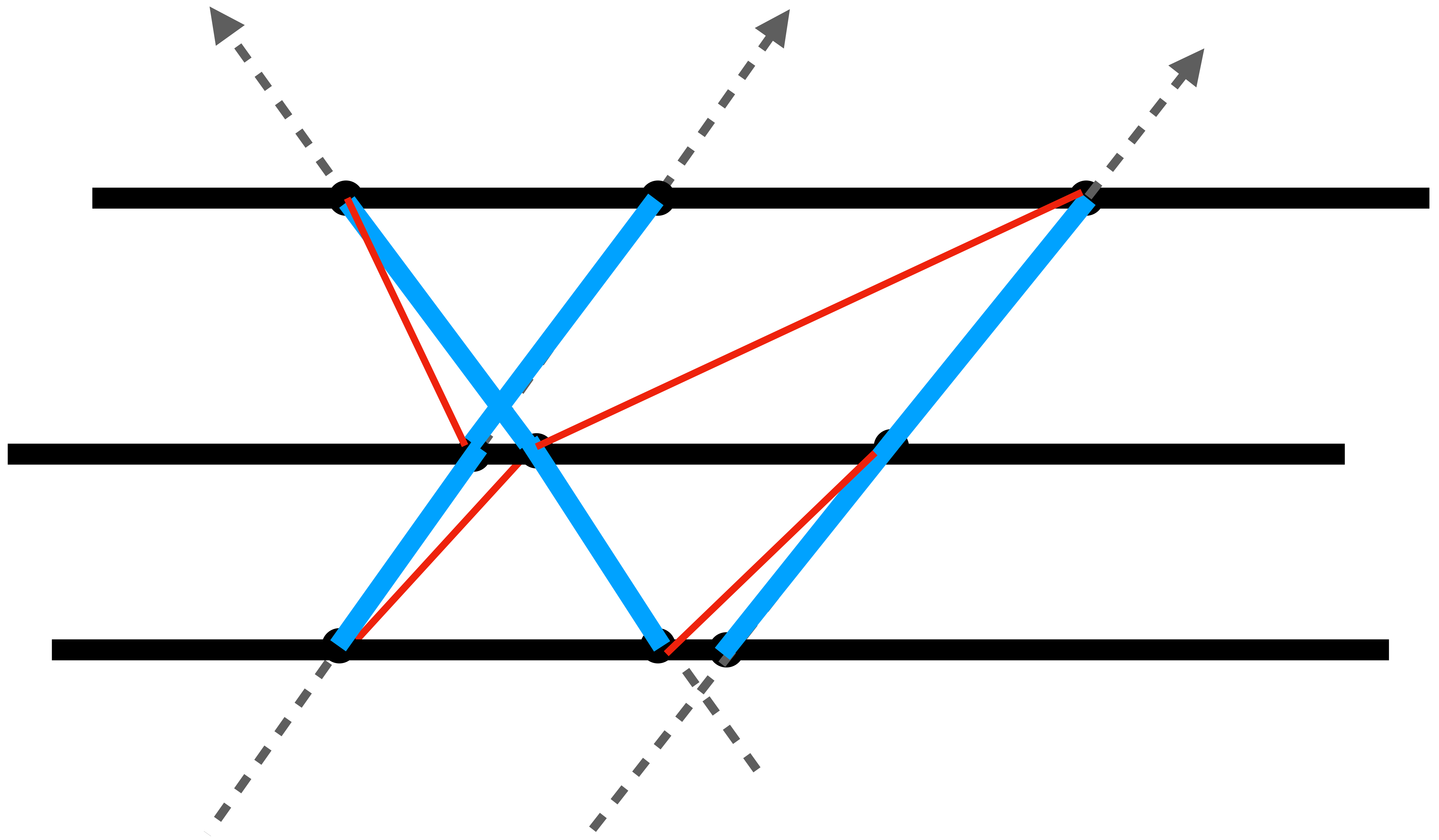


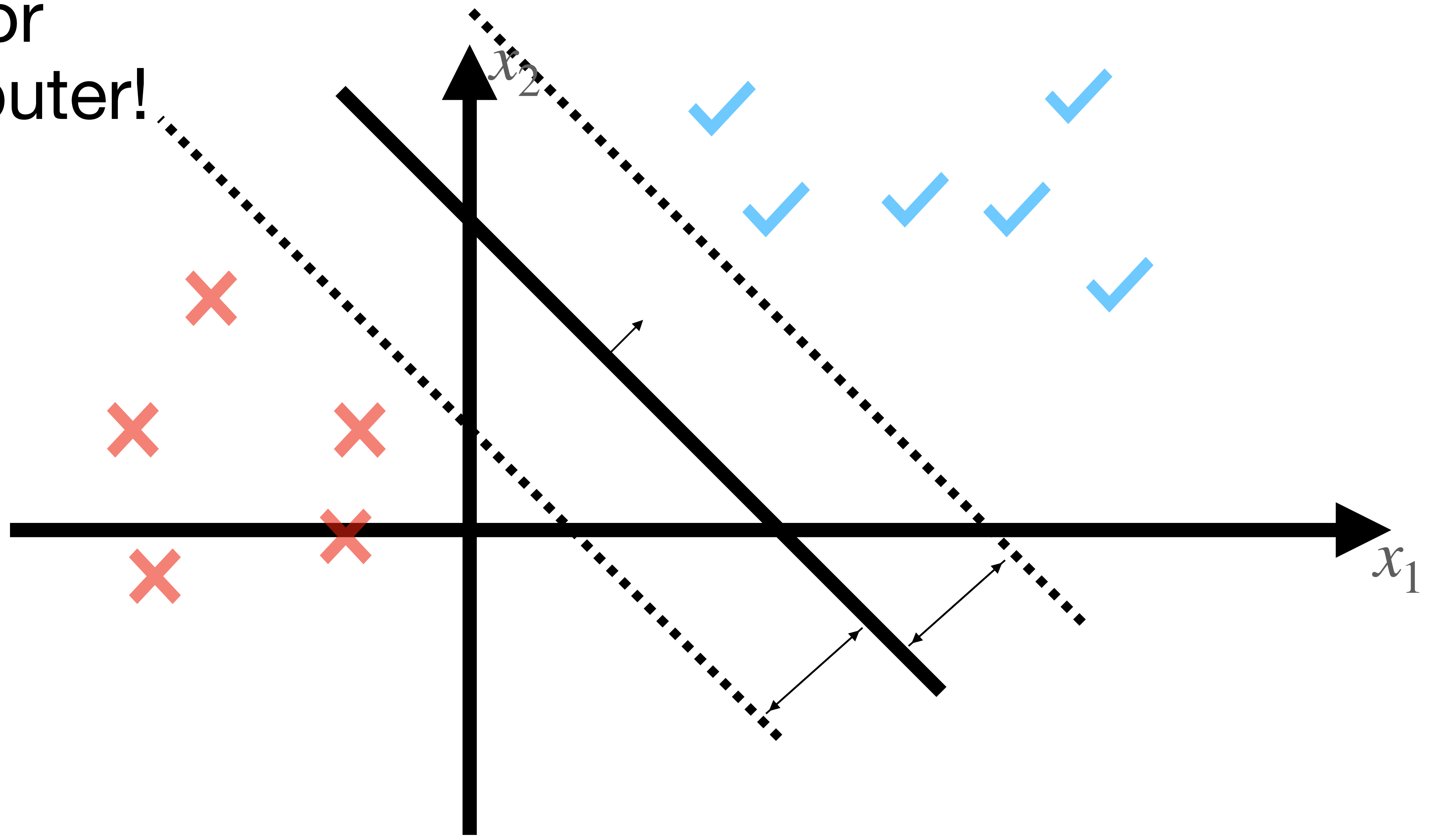


Supervised learning - **show examples to train on,** test on unseen data

Intro to **SVM**

Kernel for this with a classical or quantum computer!





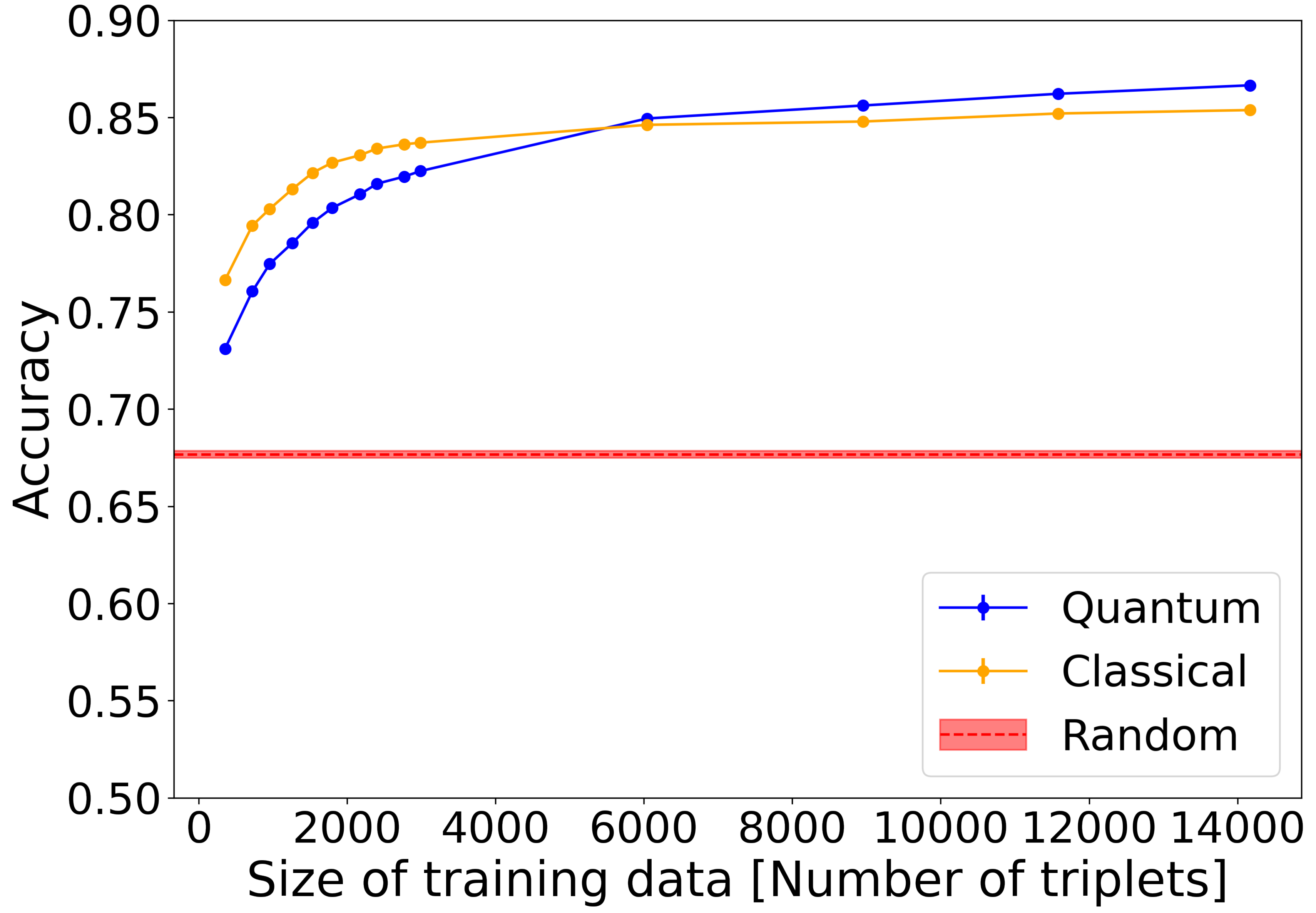
Supervised learning - show examples to train on, **test on unseen data**

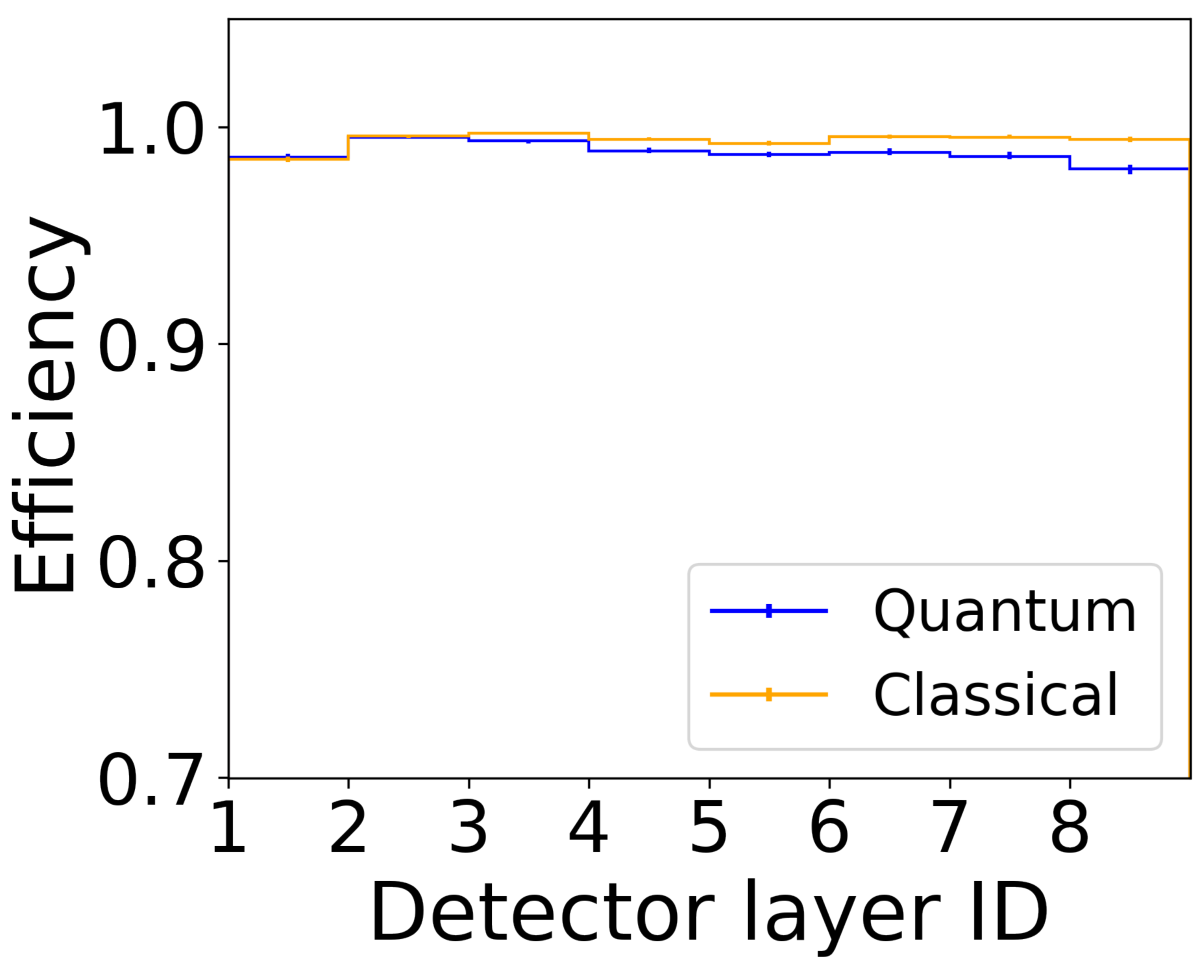
NOTE: All results shown here are obtained on a *classical computer pretending to be a quantum computer*

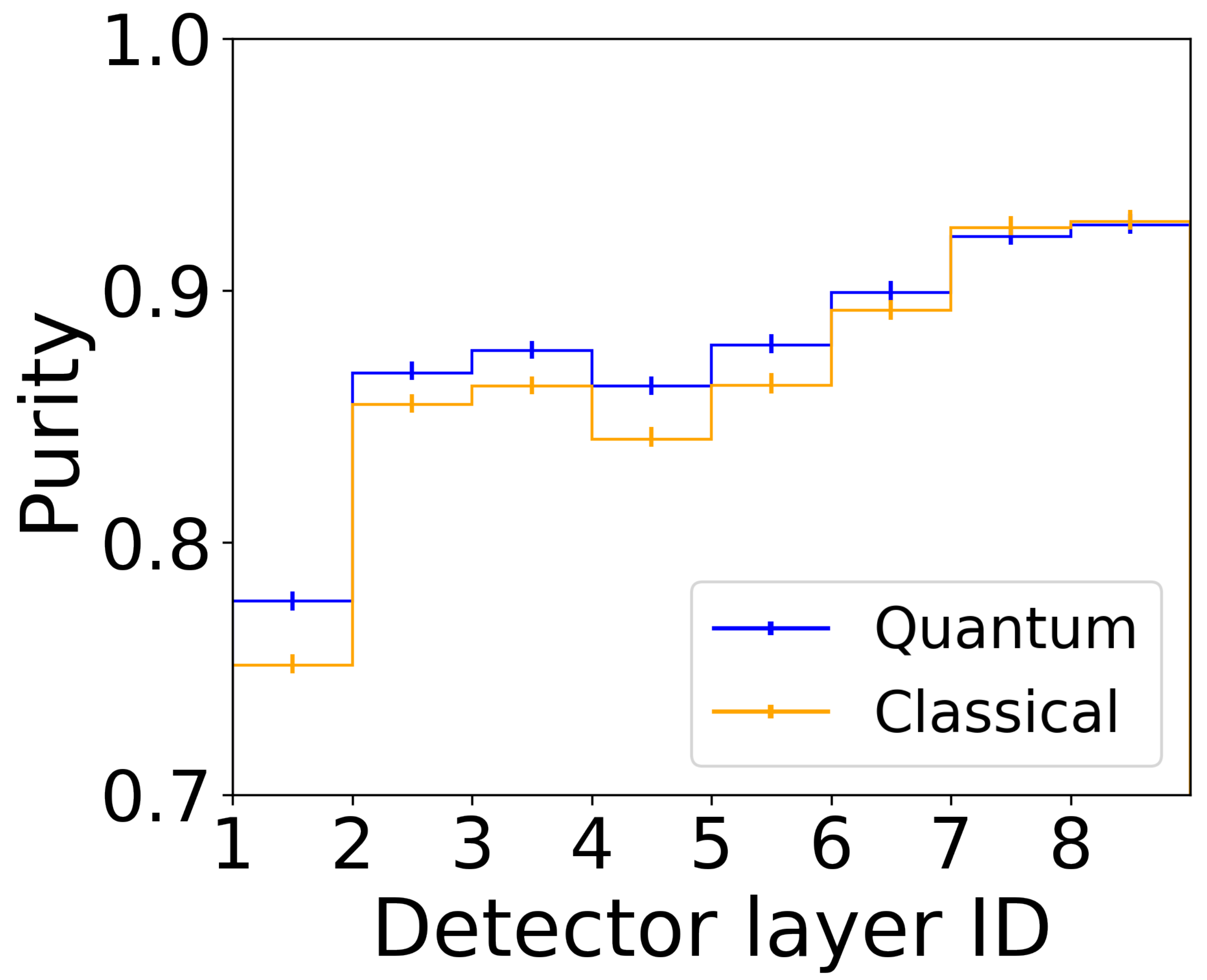
(We are running on hardware but no worthy results yet)

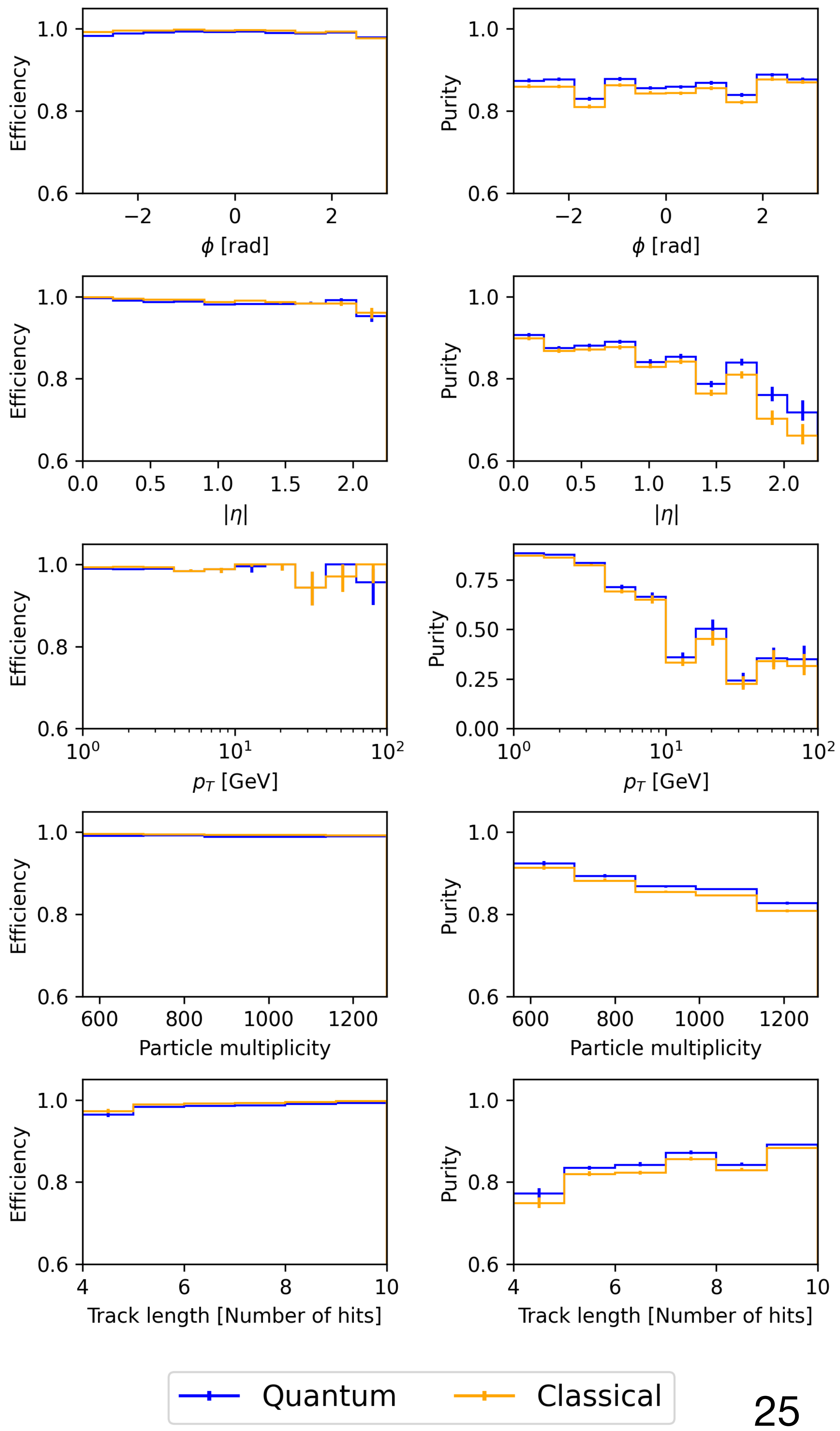
Results

Train on up to 50 events



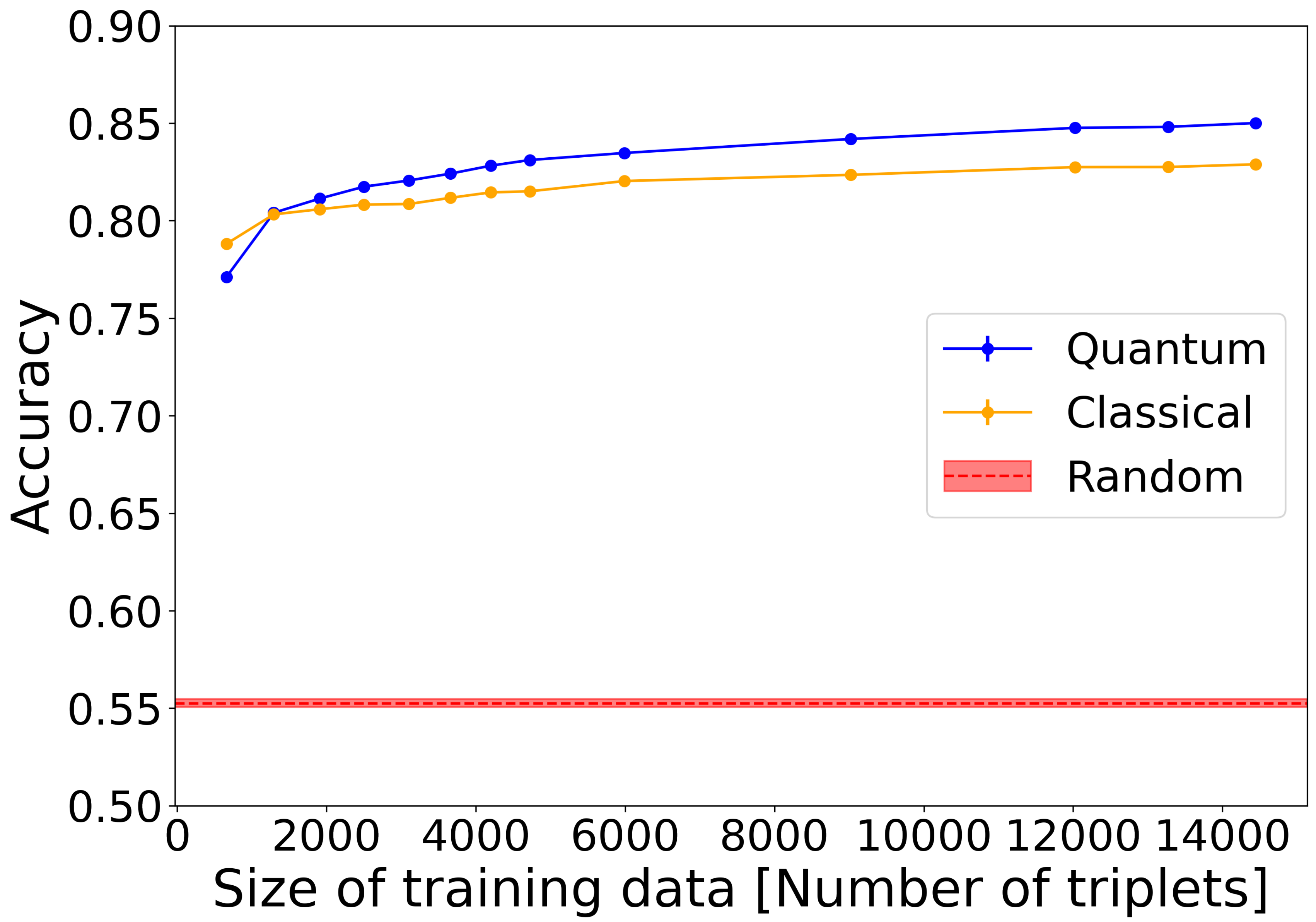


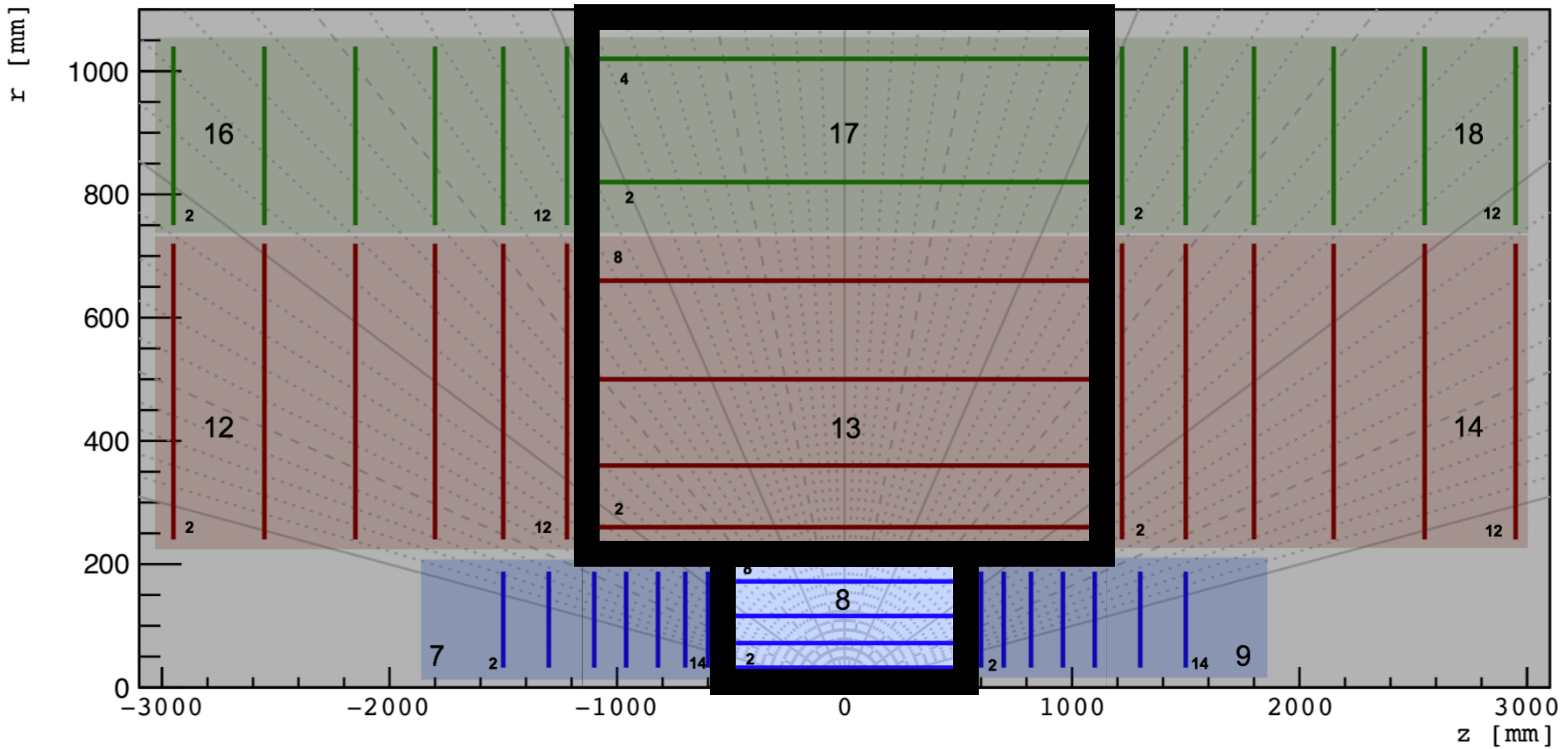


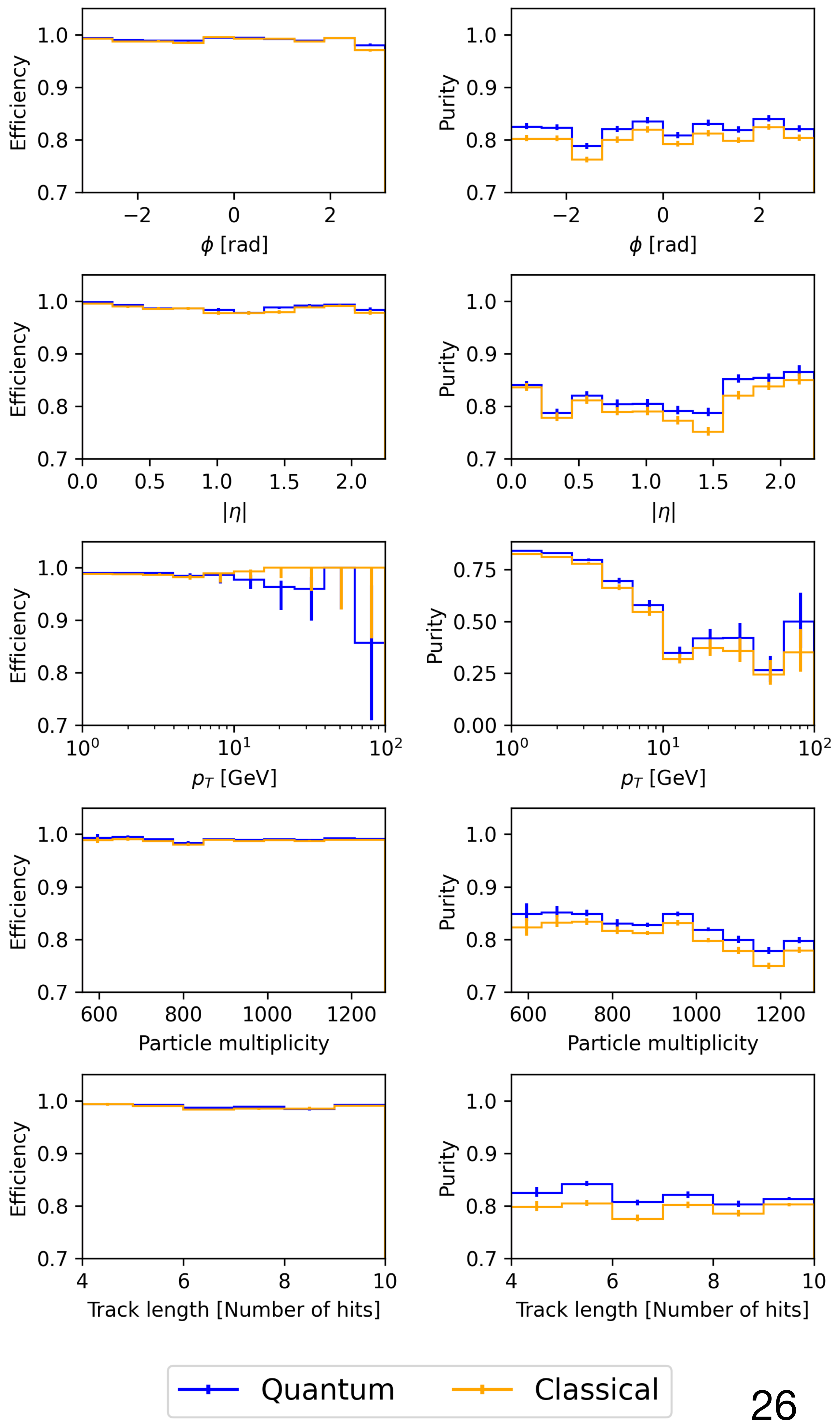


Results

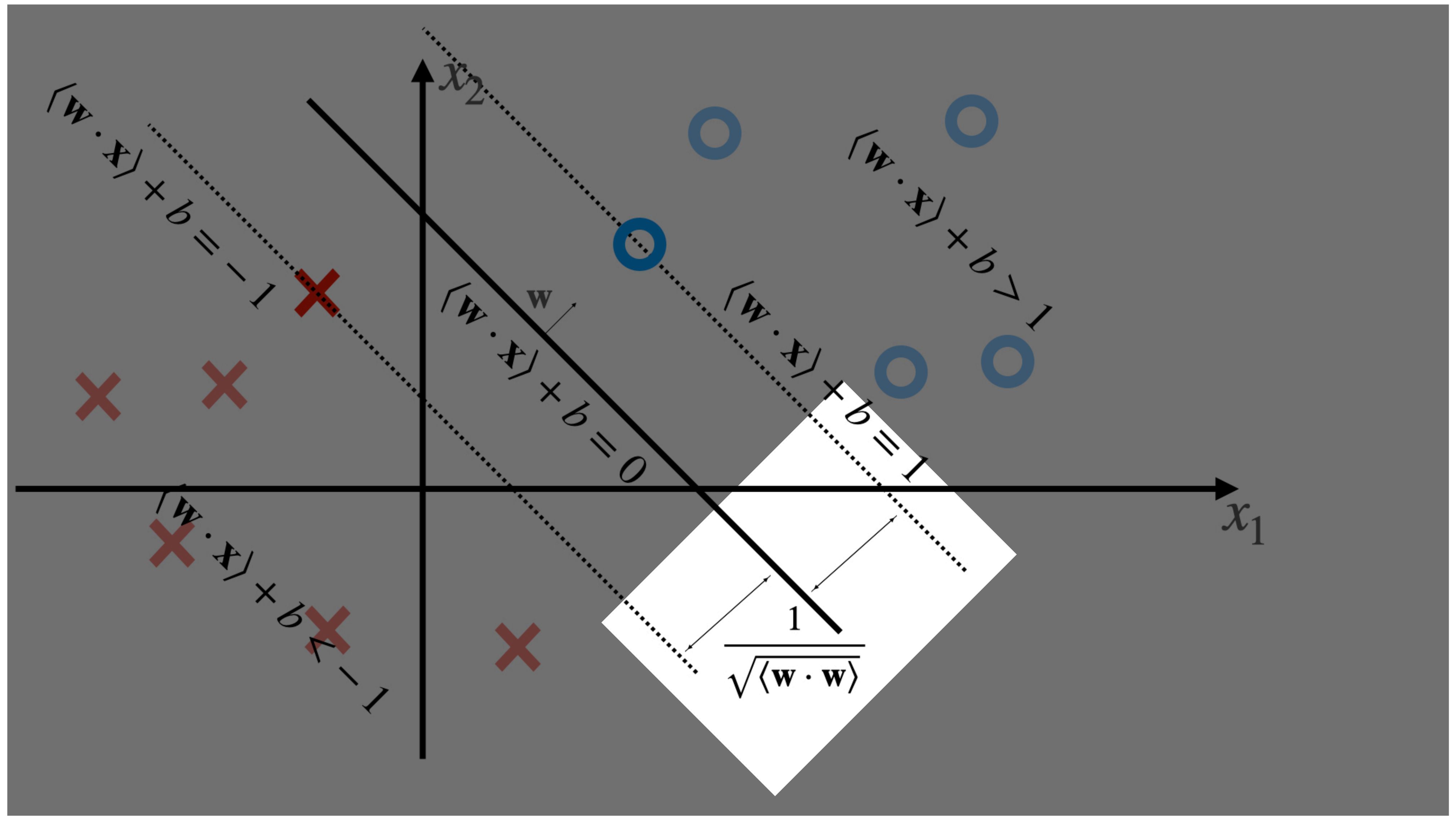
Train on up to 240 events



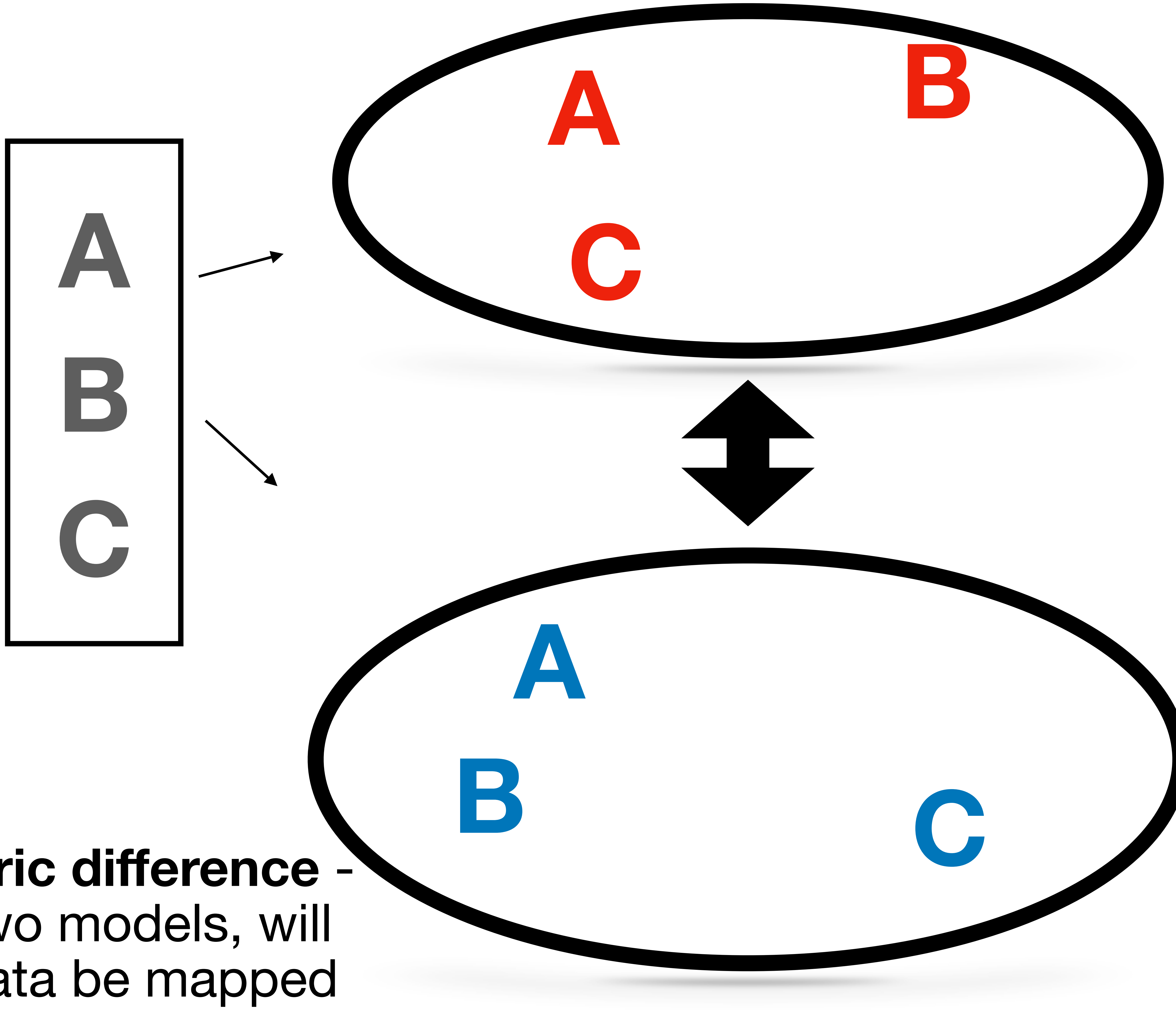




BONUS: Complexity



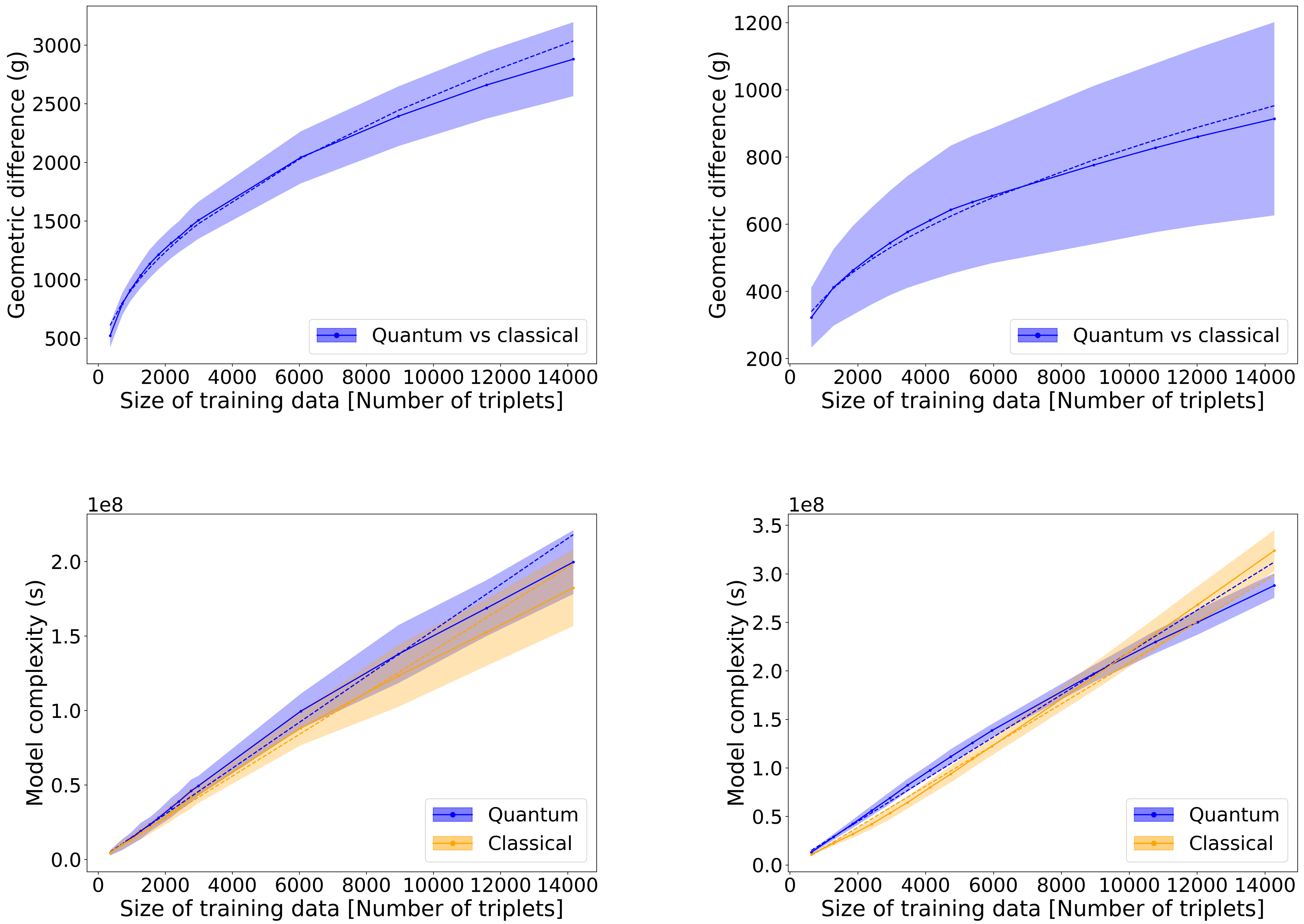
Complexity - how narrow is the margin?



Geometric difference - given two models, will same data be mapped similarly?

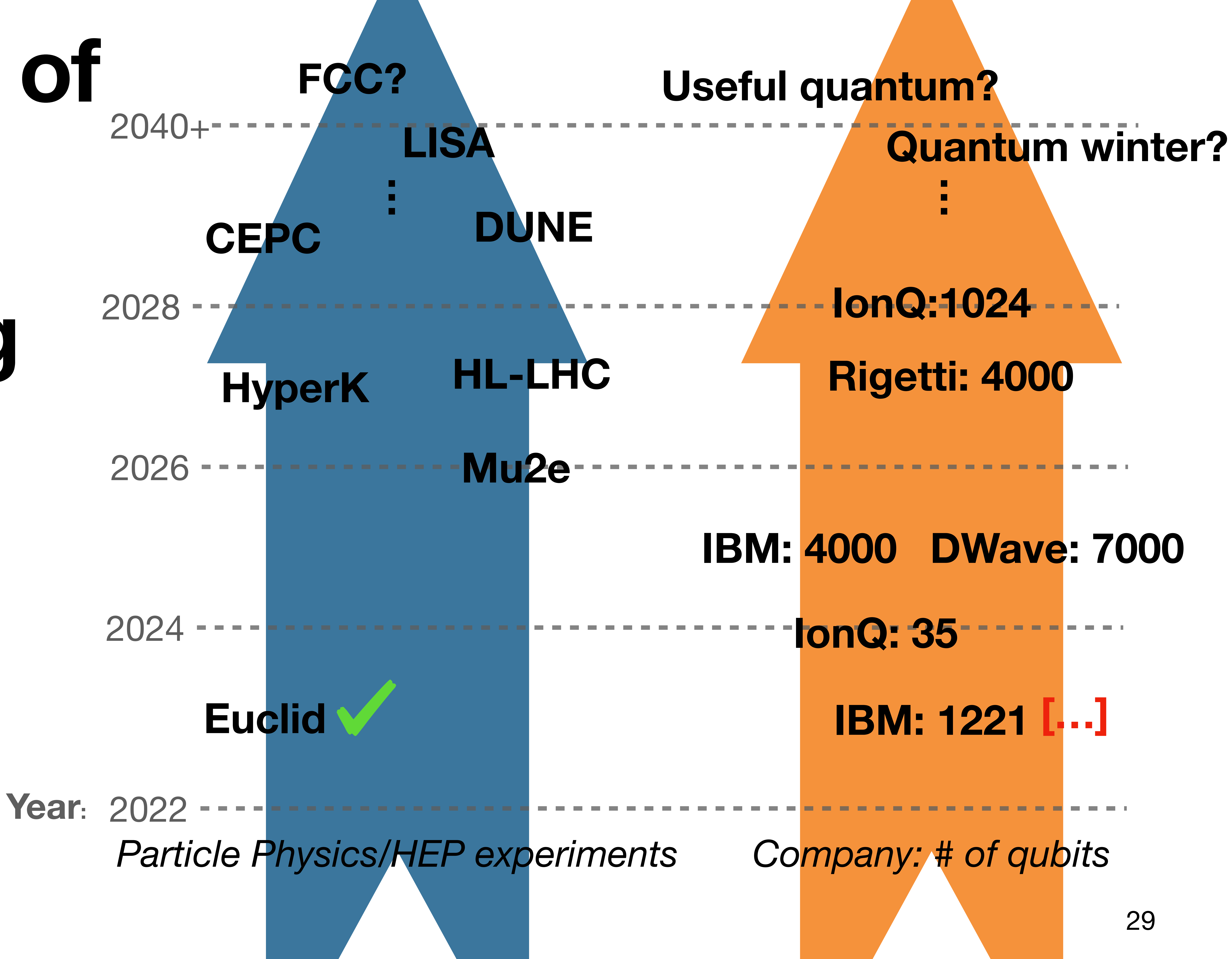
BONUS: Complexity results

Quantum kernel sufficiently different and less complex!



The future of HEP and quantum computing

But error mitigation and error correction will be necessary



Thank you


Connecting
The Dots 2023
8th International CTD Workshop
Université Paul Sabatier, Toulouse, France
10-13 October 2023
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- Slide 3 top right pic: https://www.nature.com/articles/s41566-023-01272-3
- Slides 5-10: https://arxiv.org/abs/2307.03236
- Slides 17/18: trackml logo https://www.kaggle.com/competitions/trackml-particle-identification/overview
- Slide 35: https://arxiv.org/abs/1804.11326
- Slide 37: https://quantumtech.blog/2022/10/20/quantum-computing-modalities-a-qubit-primer-revisited/

BONUS: Main cons/ pros

Algorithmic complexity (M^2)

Most tangible possibility for proven advantage

The shots with data scaling means most likely need a more sophisticated implementation

Feature mapping (thus kernels) very natural for quantum computers

No chance of advantage until larger number of features

IBM takes kernel methods seriously (paper estimating runtimes). They suggest collaboration with kernel methods experts

BONUS: Areas of current/future focus

Quantum autoencoders

Collaboration

Running on hardware

Generative models

BONUS: What’s needed for advantage?

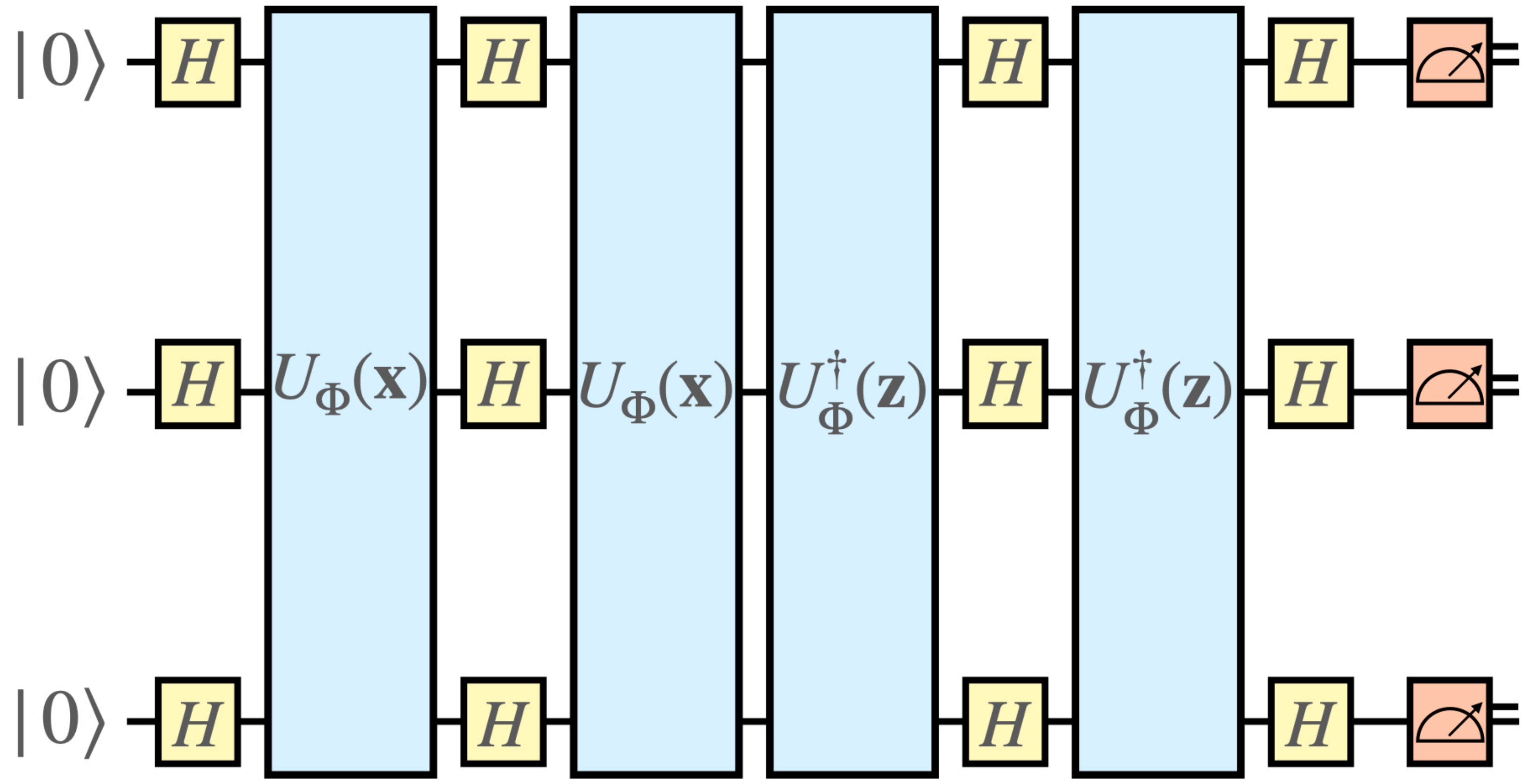
Algorithm

Use case

[probably] Error correction

[maybe] error mitigation

BONUS: Advantage from kernels - forrelation



bent-function and it's dual. It can be shown that with respect to this oracle there is an exponential separation in query complexity over classical query algorithms.

The final circuit we implement to estimate the overlap $|\langle \Phi(\boldsymbol{x}) | \Phi(\boldsymbol{y}) \rangle|^2$, c.f. Fig 5 b) is still larger. This circuit has four layers of Hadamard gates and 3 diagonal layers. A circuit that has this kind of structure is related to a problem introduced by Aaronson and Ambainis [8]. The problem is referred to k-fold Forrelation, c.f. [8], section 1.1.3. where given k total Boolean functions $f_i : \{0,1\} \to \{+1,-1\}$, $i = 1 \ldots k$ one has to decide, whether the sum

$$F_{f_1,f_2,\ldots,f_k} = \frac{1}{2^{(k+1)n/2}} \sum_{x_1,\ldots x_k \in \{0,1\}^n} f_1(x_1)(-1)^{x_1 \circ x_2} f_2(x_2)(-1)^{x_2 \circ x_3} \ldots (-1)^{x_{k-1} \circ x_k} f_k(x_k), \quad (35)$$

satisfies $|F_{f_1,f_2,\ldots,f_k}| \leq 100^{-1}$ or whether $F_{f_1,f_2,\ldots,f_k} \geq 3/5$, promised that one of these holds. The authors show, that any classical, randomized algorithm that has only black box access to the Boolean functions must make $\mathcal{O}(2^{n/2} n^{-1})$ queries to these black box functions to solve the problem. However, a quantum computer is able to solve this problem with k queries (in fact only $\lceil k/2 \rceil$ queries) to a phase oracle that encodes the Boolean function through

phase gates $U_{\Phi(\boldsymbol{x})}$, $U^\dagger_{\Phi(\boldsymbol{y})} U_{\Phi(\boldsymbol{x})}$ and $U^\dagger_{\Phi(\boldsymbol{y})}$ assume the roles of the oracles U_{f_1} U_{f_2} and U_{f_3} queried in 3-fold Forrelation respectively. Hence, the kernel estimation we perform here is directly related to the Forrelation problem by Aaronson and Ambainis.

BONUS:Cluster computers

DELL PowerEdge servers, 15 with two six-core Intel Xeon E5-2430 2.7 GHz CPUs and 48GB of RAM, 11 with two eight-core Intel Xeon E5-2620 3.0 GHz CPUs and 64GB of RAM or better.

BONUS: qubit modalities

Qubit Type	Pros/Cons	Select Players
Superconducting	***Pros***: High gate speeds and fidelities. Can leverage standard lithographic processes. Among first qubit modalities so has a head start. ***Cons***: Requires cryogenic cooling; short coherence times; microwave interconnect frequencies still not well understood.	rigetti, Google, IBM Q, QuTech, OQC, IQM, qci Quantum Circuits, Inc, 本源量子 Origin Quantum
Trapped Ions	***Pros***: Extremely high gate fidelities and long coherence times. Extreme cryogenic cooling not required. Ions are perfect and consistent. ***Cons***: Slow gate times/ operations and low connectivity between qubits. Lasers hard to align and scale. Ultra-high vacuum required. Ion charges may restrict scalability.	IONQ, AQT, QUANTINUUM, oxford ionics, Universal Quantum
Photonics	***Pros***: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuums required. Small overall footprint. Can leverage existing CMOS fabs. ***Cons***: Noise from photon loss; each program requires its own chip. Photons don't naturally interact so 2Q gate challenges.	PsiQuantum, XANADU, QUIX QUANTUM, ORCA Computing
Neutral Atoms	***Pros***: Long coherence times. Atoms are perfect and consistent. Strong connectivity, including more than 2Q. External cryogenics not required. ***Cons***: Requires ultra-high vacuums. Laser scaling challenging.	ColdQuanta, QuEra COMPUTING INC., atom computing, PASQAL
Silicon Spin/Quantum Dots	***Pros***: Leverages existing semiconductor technology. Strong gate fidelities and speeds. ***Cons***: Requires cryogenics. Only a few entangled gates to-date with low coherence times. Interference/cross-talk challenges.	intel, Silicon Quantum Computing, diraq, QUANTUM MOTION, QUANTUM BRILLIANCE