Quantum Computing in High Energy Physics

Examples from CERN

QUANTUM
TECHNOLOGY
INITIATIVE

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2023 CERN-Fermilab HCP Summer School– CERN, June 22nd, 2023

Outline

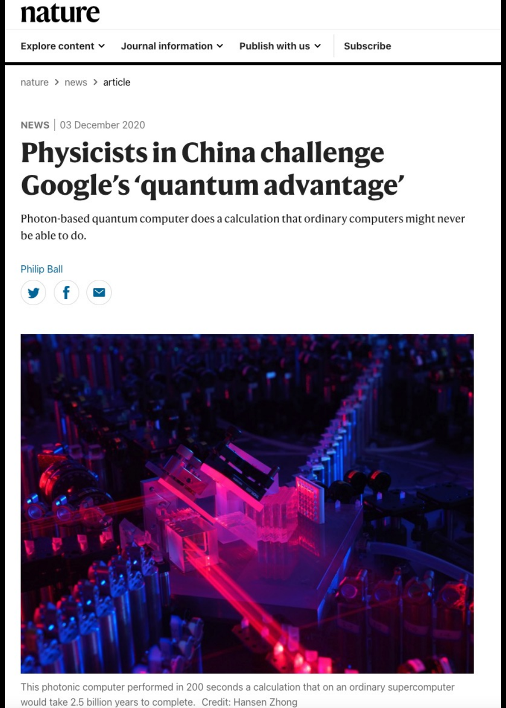
- Introduction
  - Bell Inequalities & Quantum Technologies
- Quantum Computing
  - Qubits and Quantum Computers architectures
  - Quantum algorithms
- The CERN Quantum Technology Initiative
- Quantum Machine Learning and Applications at CERN
  - Anomaly Detection
  - Beam Optimisation in linear accelerators
- Summary & Outlook

Hype and Potential…

2019: Google

https://www.nature.com/articles/s41586-019-1666-5

2020: Hefei National Lab



NEWS | 03 December 2020

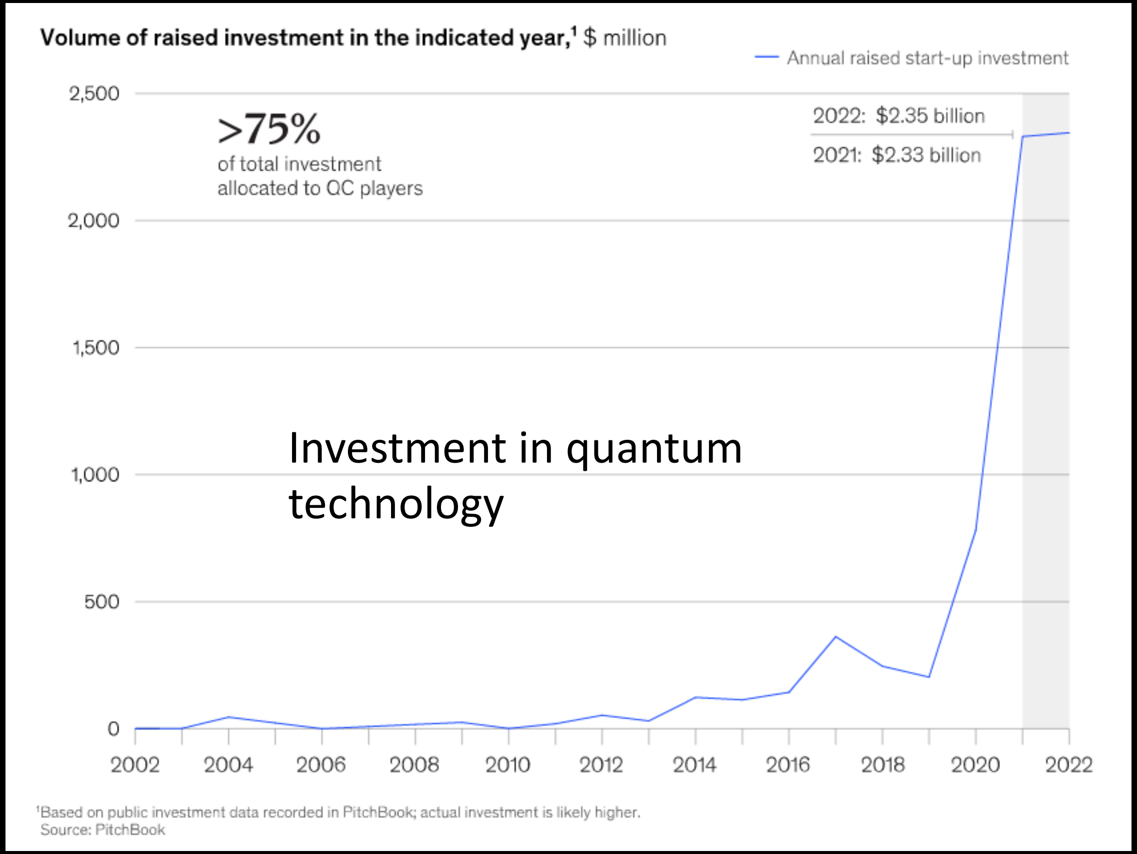
Physicists in China challenge Google's 'quantum advantage'

Photon-based quantum computer does a calculation that ordinary computers might never be able to do.

Philip Ball

This photonic computer performed in 200 seconds a calculation that on an ordinary supercomputer would take 2.5 billion years to complete. Credit: Hansen Zhong

https://www.nature.com/articles/d41586-020-03434-7



Investment in quantum technology

[1] Based on public investment data recorded in PitchBook; actual investment is likely higher.
Source: PitchBook

Source: McKinsey 2023
https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-technology-sees-record-investments-progress-on-talent-gap

NOBELPRISET I FYSIK 2022
THE NOBEL PRIZE IN PHYSICS 2022

Alain Aspect
Université Paris-Saclay &
École Polytechnique, France

John F. Clauser
J.F. Clauser & Assoc.,
USA

Anton Zeilinger
University of Vienna,
Austria

”för experiment med sammanflätade fotoner som påvisat brott mot Bell-olikheter och banat väg för kvantinformationsvetenskap”

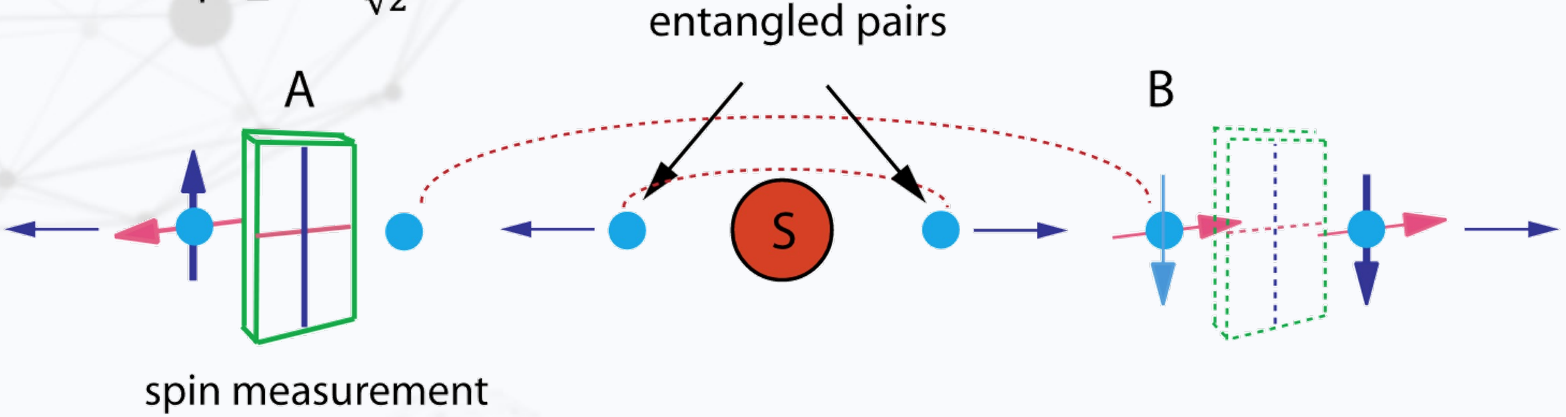
“for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”

https://youtu.be/mtgYG2zsbbQ

www.nobelprize.org

Einstein Podolsky Rosen Paradox

$$|\psi_\pm\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle)$$



$$[S_i, S_j] = i\hbar\epsilon^{ijk} S_k$$

For arbitrary **a,b** measurement directions the probability to measure oppposite spin values is

$$\tfrac{1}{2}(1+\vec{a}\cdot\vec{b})$$

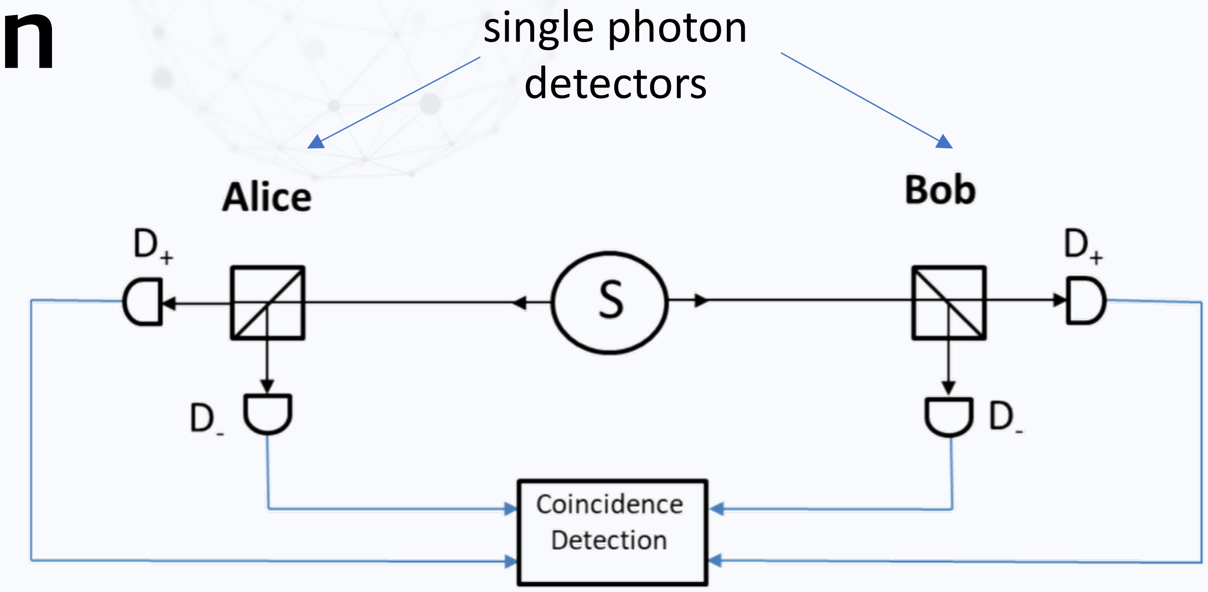
- 1935: EPR paradox questions completeness of Quantum Mechanics

‘From this follows that either (1) the quantum-mechanical description of reality given by the wave function is not complete or (2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality’

A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47, 777 (1935)

Bell Inequalities and the second quantum revolution

- 1964: Bell inequality are a mathematical proof that no theory based on **local hidden variables** (realism) can reproduce QM results
- 1969: Clauser, Horne, Shimony (CHSH) formulation
- 1972 Freedman & Clauser experiment
- 1976-1982 Aspects experiments
- Measure the correlation across the possible outcomes of multiple measurements in A and B
- «Classical» (local realist) theory predicts bound correlation
- It is possible to design experimental conditions in which QM violates the bound



Second Quantum Revolution
Use distant entangled photons as a quantum reource

  - No clone theorem
  - Quantum networks and teleportation

Many particles entanglement

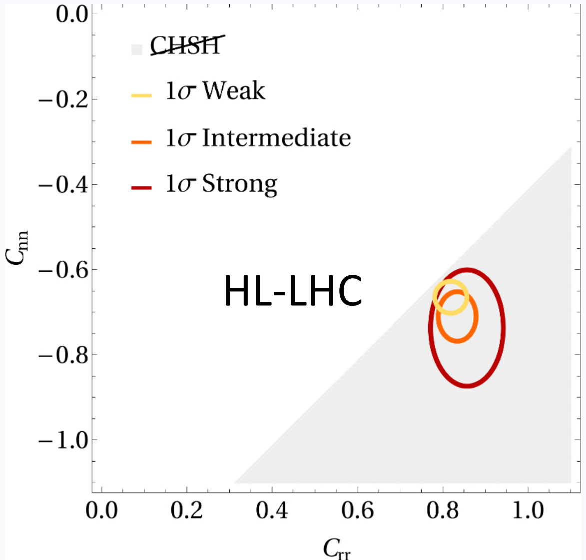
  - Computing and criptography

Bell Inequalities tests at colliders

- Multiple tests at colliders over the years at different energy scales
- Recent proposals at the LHC / HL-LHC:
  - Fabbrichesi et al. "Testing Bell inequalities at the LHC with top-quark pairs." *Physical Review Letters* 127.16 (2021): 161801.
  - Severi et al. "Quantum tops at the LHC: from entanglement to Bell inequalities." *The European Physical Journal C* 82.4 (2022): 285
  - Aguilar-Saavedra and Casas. "Improved tests of entanglement and Bell inequalities with LHC tops." *The European Physical Journal C* 82.8 (2022): 666
  - Aguilar-Saavedra et al. "Testing entanglement and Bell inequalities in H→ Z Z." *Physical Review D* 107.1 (2023): 016012
  - Barr, Alan J. "Testing Bell inequalities in Higgs boson decays." Physics Letters B 825 (2022): 136866

$t\bar{t}$ production at hadron colliders:

- Leading mechanism generates top spins that are highly correlated
- Tops decay semi-weakly before spin is randomised
- Charged lepton from $t \to Wb$, $W \to \ell \nu$ is 100% correlated with top spin



Severi, Claudio, et al. "Quantum tops at the LHC: from entanglement to Bell inequalities." *The European Physical Journal C* 82.4 (2022): 285

Quantum Technology

First Quantum Revolution

Max Planck black-body radiation

Transistor, laser, atomic clock, computers, optical fibre communication, …

1900

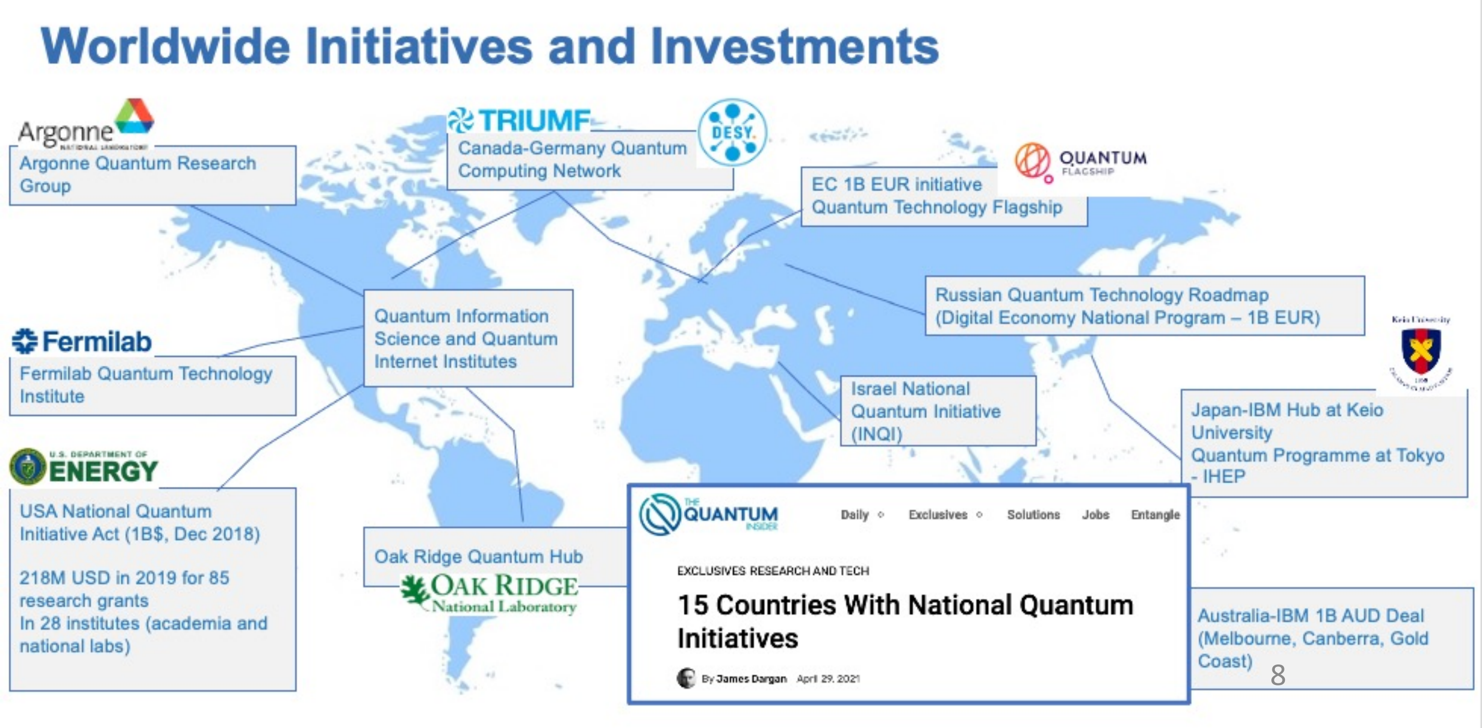
2000

Second quantum revolution

Use quantum mechanics principles to develop new technology

“Artificial” quantum states

Now



Worldwide Initiatives and Investments

Argonne Quantum Research Group

Canada-Germany Quantum Computing Network

EC 1B EUR initiative Quantum Technology Flagship

Quantum Information Science and Quantum Internet Institutes

Russian Quantum Technology Roadmap (Digital Economy National Program – 1B EUR)

Fermilab Quantum Technology Institute

Israel National Quantum Initiative (INQI)

Japan-IBM Hub at Keio University
Quantum Programme at Tokyo - IHEP

USA National Quantum Initiative Act (1B$, Dec 2018)

218M USD in 2019 for 85 research grants
In 28 institutes (academia and national labs)

Oak Ridge Quantum Hub

THE QUANTUM INSIDER

Daily ◦ Exclusives ◦ Solutions Jobs Entangle

EXCLUSIVES RESEARCH AND TECH

15 Countries With National Quantum Initiatives

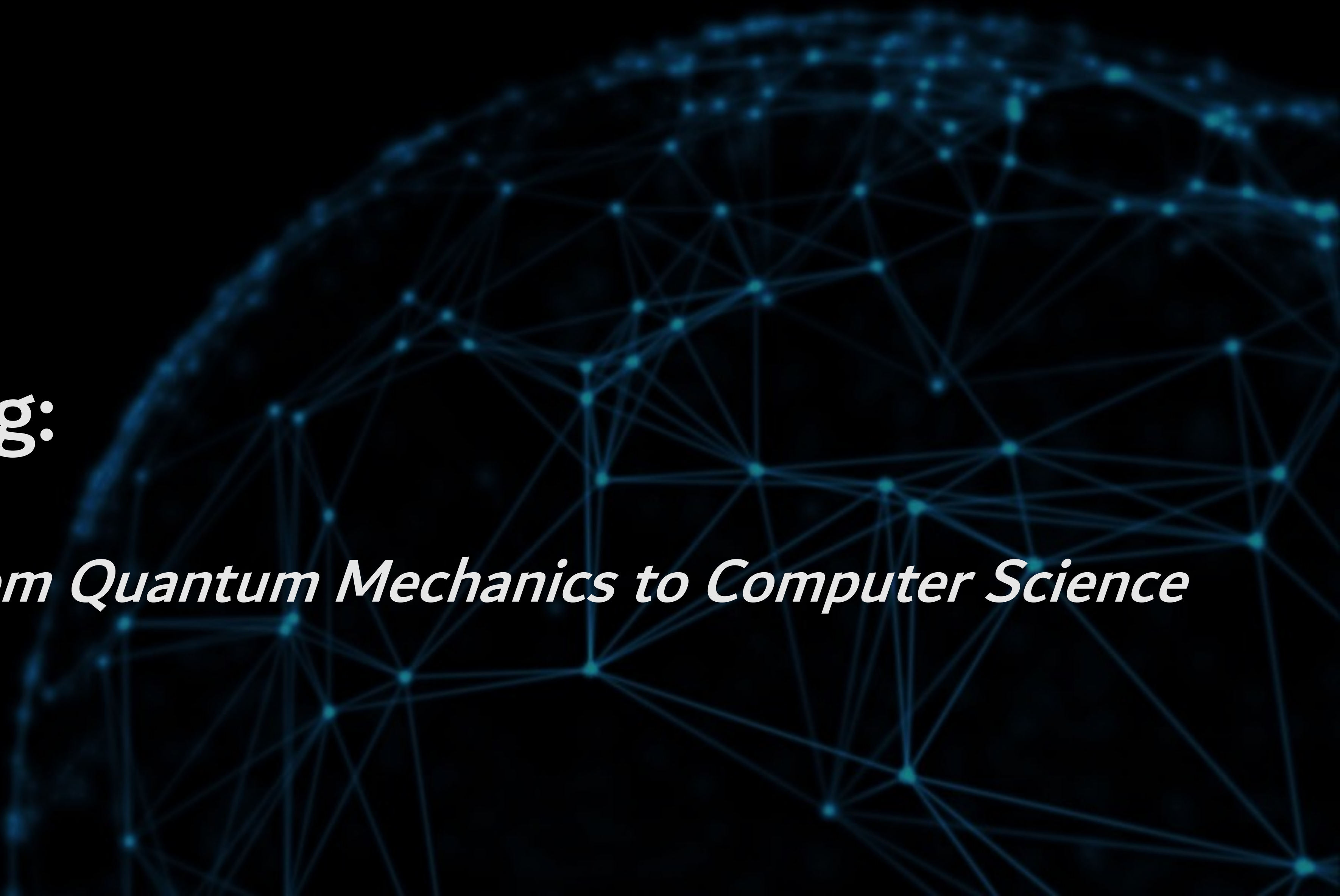
By James Dargan April 29, 2021

Australia-IBM 1B AUD Deal (Melbourne, Canberra, Gold Coast)

Dowling & Milburn. "**Quantum technology: the second quantum revolution.**" *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 361.1809 (2003): 1655-1674.

Quantum Computing:

From Quantum Mechanics to Computer Science



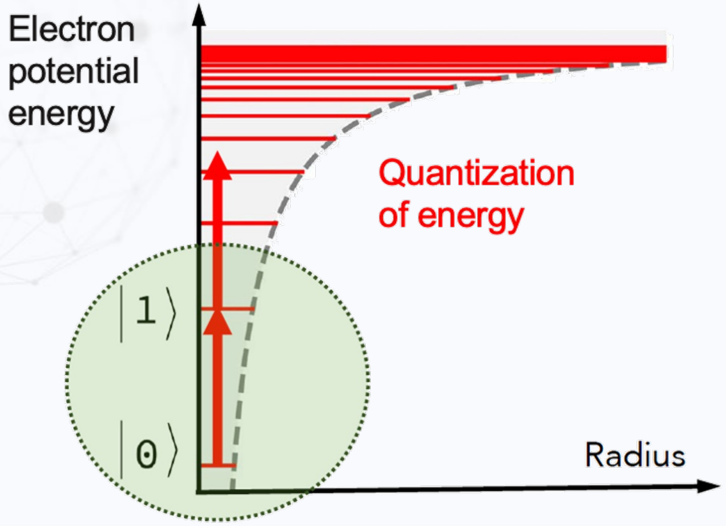
Qubit: Quantum Bit

- Basic Unit of Quantum Computation representation
  - **Classical bits are binary** “0 or 1”
- Quantum Mechanics predicts **superposition states (exponential storage information)**
- **Dirac notation** is used to describe quantum states

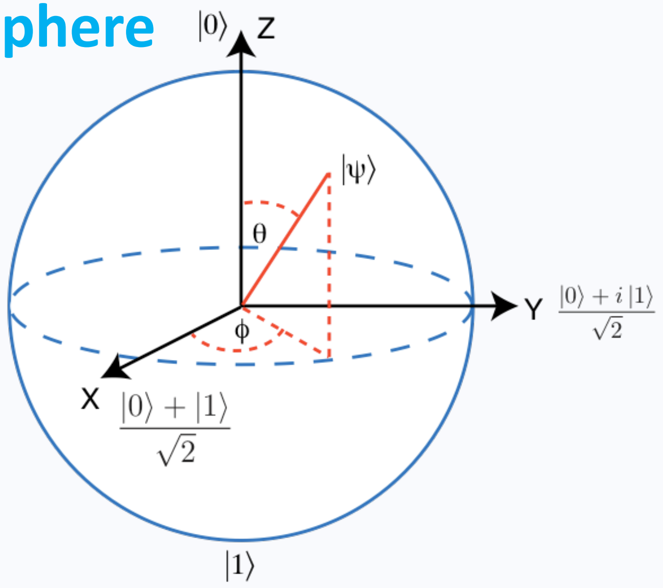
$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

$$\alpha, \beta \in C^2 \qquad |\alpha|^2 + |\beta|^2 = 1$$

Interest in **multi level** representations: qutrits..



Bloch Sphere



$$|\psi\rangle = \cos\tfrac{\theta}{2}\,|0\rangle + e^{i\varphi}\sin\tfrac{\theta}{2}\,|1\rangle$$

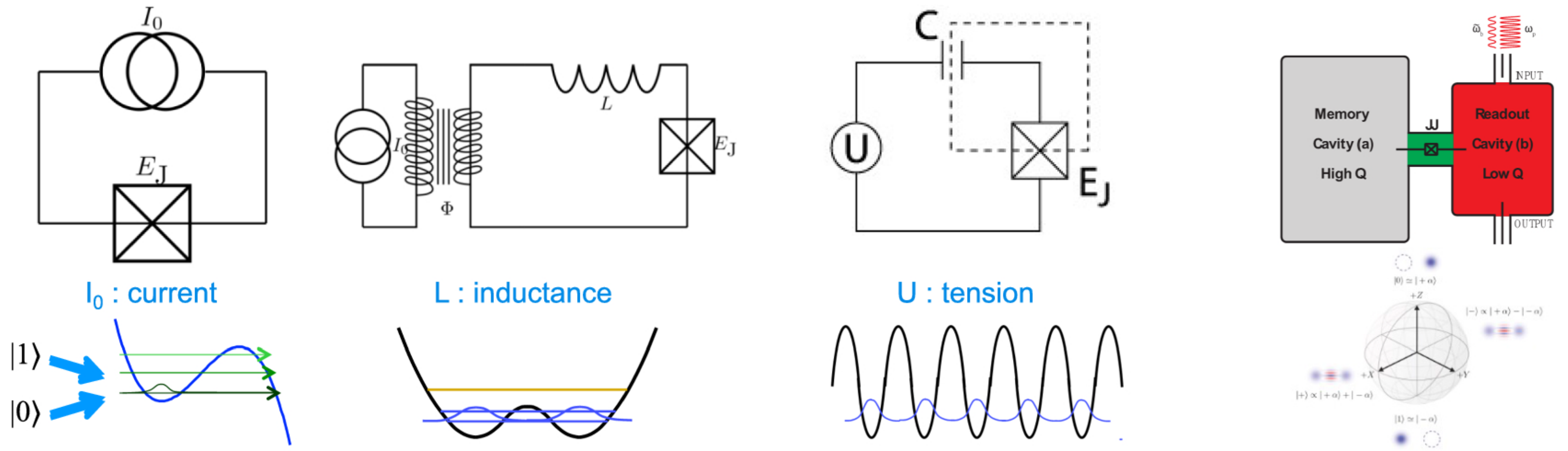
Quantum Computing

Principles of quantum mechanics enhance computations

- **Superposition** leads to parallelism → **exponential speedup?**
- **Entanglement** → **non linear correlation and classical simulability?**
- Operations (gates) are unitary transformations → **reversible computing?**
- Output is the result of a quantum state measurement according to Born rule → **stochastic computation ?**
- **No-cloning theorem** → **information security**
- **Quantum state coherence and isolation** → **computation stability and errors**
- **Qubit state collapses** → **reproducibility?**

Superconducting Qubits

Ezratty, O. **Perspective on superconducting qubit quantum computing**. Eur. Phys. J. A 59, 94 (2023). https://doi.org/10.1140/epja/s10050-023-01006-7



(cc) Olivier Ezratty, 2023

	phase qubit	flux qubit	charge qubit - transmon	cat-qubits
	Josephson junctions handle the qubit degree of liberty			Josephson junctions prepare, couple and correct the cat-qubits
|0⟩ and |1⟩ qubits	two energy levels in a potential well	two superconducting current directions	two levels of charge of Cooper pairs	pairs of entangled microwave photons in a cavity
quantum gates	micro-waves	magnetic field	micro-waves	micro-waves
qubits readout	resonator and micro-waves	magnetometer (SQUID)	resonator and micro-waves	resonator and micro-waves
commercial vendors	**abandonned**	D-Wave The Quantum Computing Company rigetti QILIMANJARO QUANTUM-TECH Alibaba bleximo ATLANTIC QUANTUM	IBM Google IQM OQC	ALICE & BOB qci amazon

Multiple technologies

Trapped ions

Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.

Longevity (seconds)	>1000
Logic success rate	99.9%
Number entangled	14

Company support
ionQ

Pros
Very stable. Highest achieved gate fidelities.

Cons
Slow operation. Many lasers are needed.

Silicon quantum dots

These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.

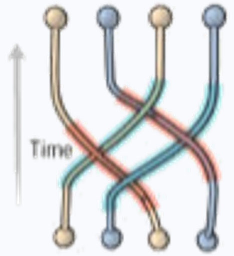
Longevity (seconds)	0.03
Logic success rate	~99%
Number entangled	2

Company support
Intel

Pros
Stable. Build on existing semiconductor industry.

Cons
Only a few entangled. Must be kept cold.

Topological qubits



Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.

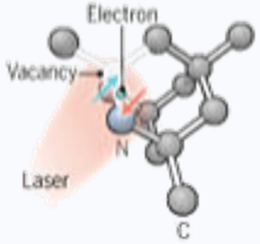
Longevity (seconds)	N/A
Logic success rate	N/A
Number entangled	N/A

Company support
Microsoft, Bell Labs

Pros
Greatly reduce errors.

Cons
Existence not yet confirmed.

Diamond vacancies



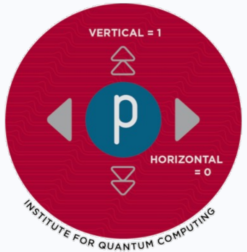
A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

Longevity (seconds)	10
Logic success rate	99.2%
Number entangled	6

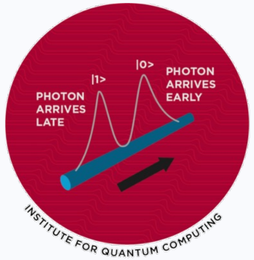
Company support
Quantum Diamond Technologies

Pros
Can operate at room temperature.

Cons
Difficult to entangle.



Polarization States



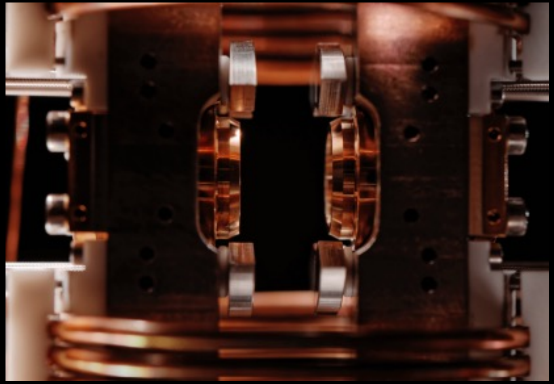
Time qubits

Path Qubits:

See Institute of Quantum Computing, U. of Waterloo, https://uwaterloo.ca/institute-for-quantum-computing/quantum-101/quantum-information-science-and-technology/what-qubit#Spin

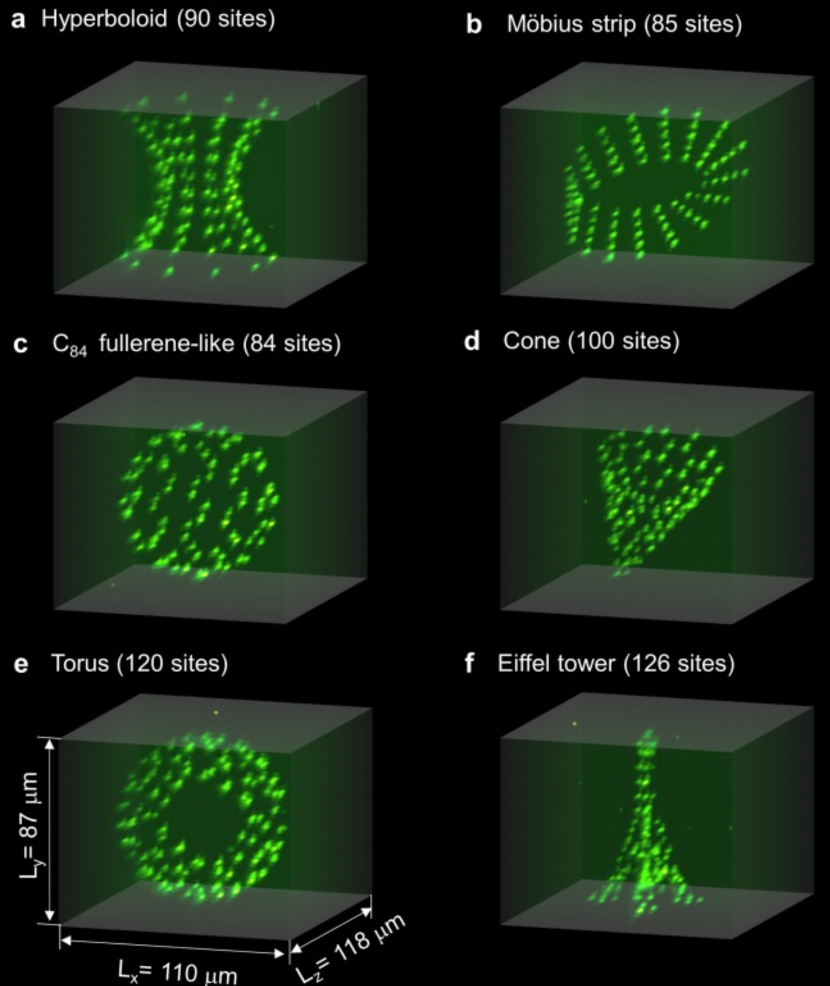
Neutral atom arrays

D. Barredo *et al.*, "Synthetic three-dimensional atomic structures assembled atom by atom." arXiv:1712.02727, 2017.



- Configurable arrays of **single neutral atoms**
- 2 energy levels represent the qubit states
- Use **lasers** to control position and the state of the atom
  - assemble and read-out registers made of **hundreds of qubits**
  - **fully programmable quantum processing**
- **High connectivity**
- Specific computation cycle because the **register is not permanently built**
  - register preparation
  - quantum processing
  - register readout

PASQAL



Gates and circuits

- Operations on qubits are **unitary** matrices describing Schrodinger state evolution
  - **Reversible operations**
  - Input and output states have the **same dimension**
  - Some classical gates (or , and, nand, xor...) **cannot be implemented directly**
  - Can **simulate** any classical computation with small overhead

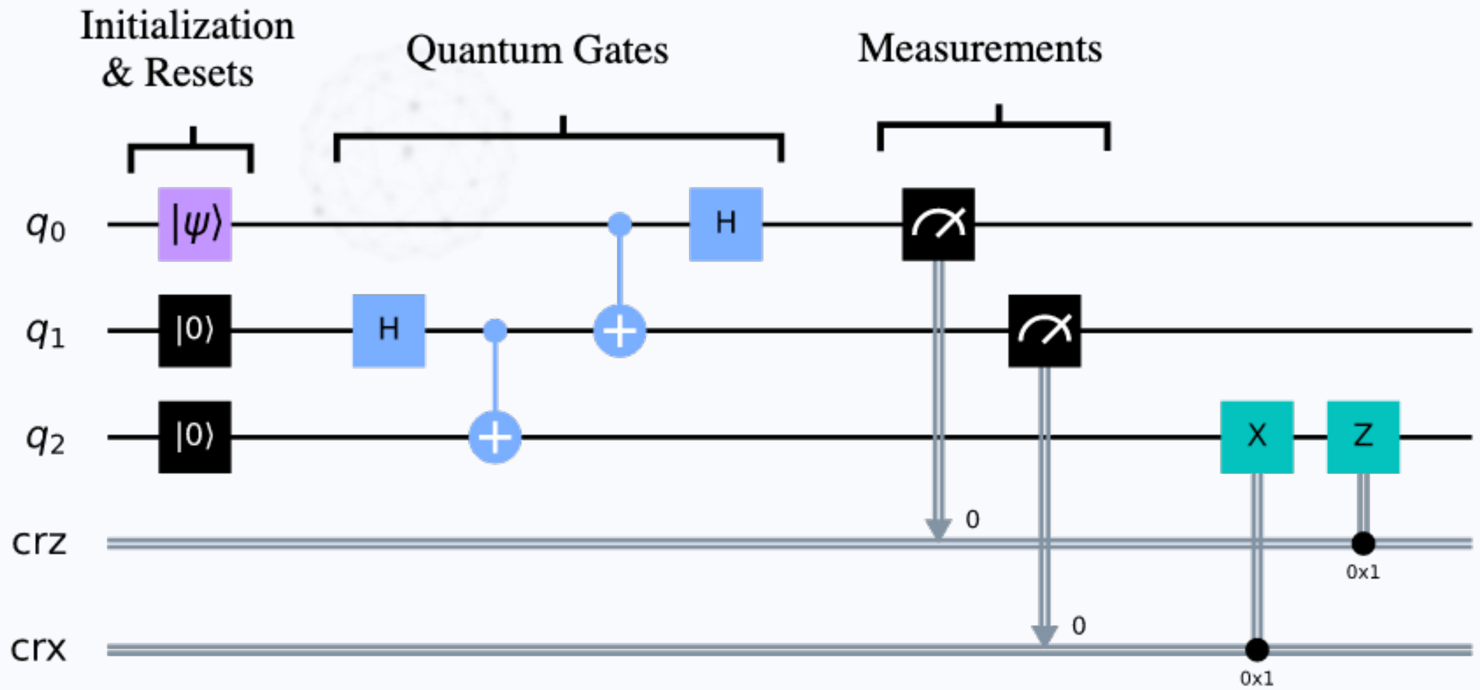


Image credits: Qiskit Textbook

Quantum Algorithms

A collection on **http://quantumalgorithmzoo.org**

- Multiple algorithms have been studied
  - Shor algorithm for **prime factorization**
  - Grover algorithm for unsorted DB **searches**
  - Quantum **Fourier Transform**
  - …
- Quantum-inspired algorithms (emulate quantum effects on classical hardware)
- Quantum Machine Learning
- Challenge is re-thinking **algorithms design** and define fair **benchmarking** and **comparison** to classical algorithms

https://quantum-computing.ibm.com/composer/docs/iqx/guide/shors-algorithm

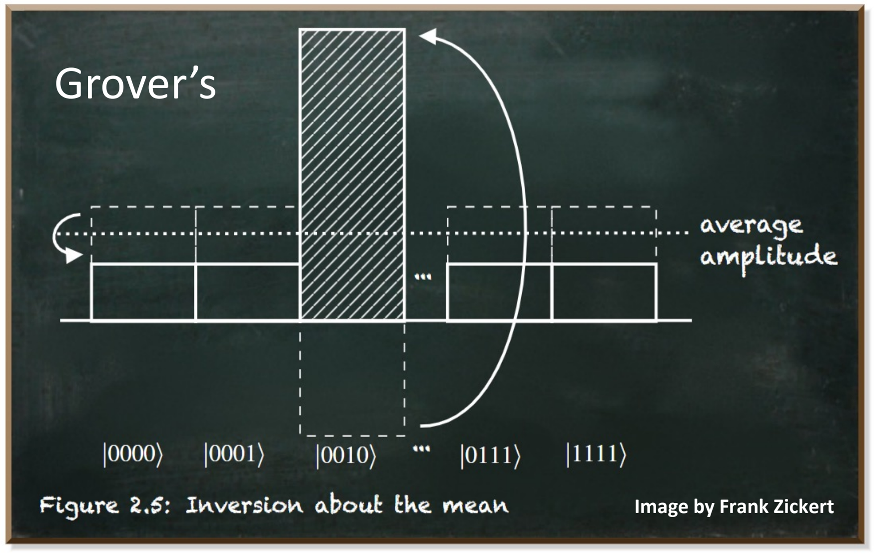


Figure 2.5: Inversion about the mean

Image by Frank Zickert

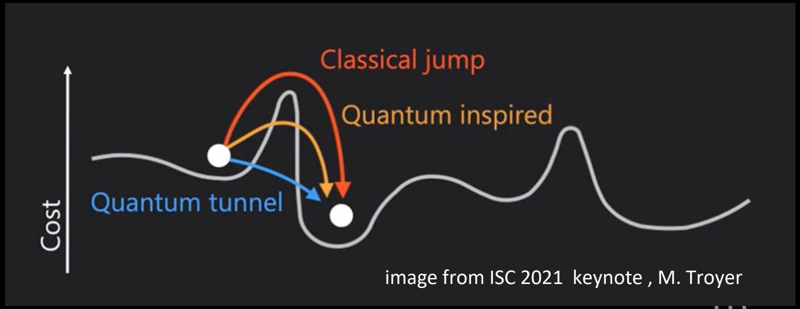
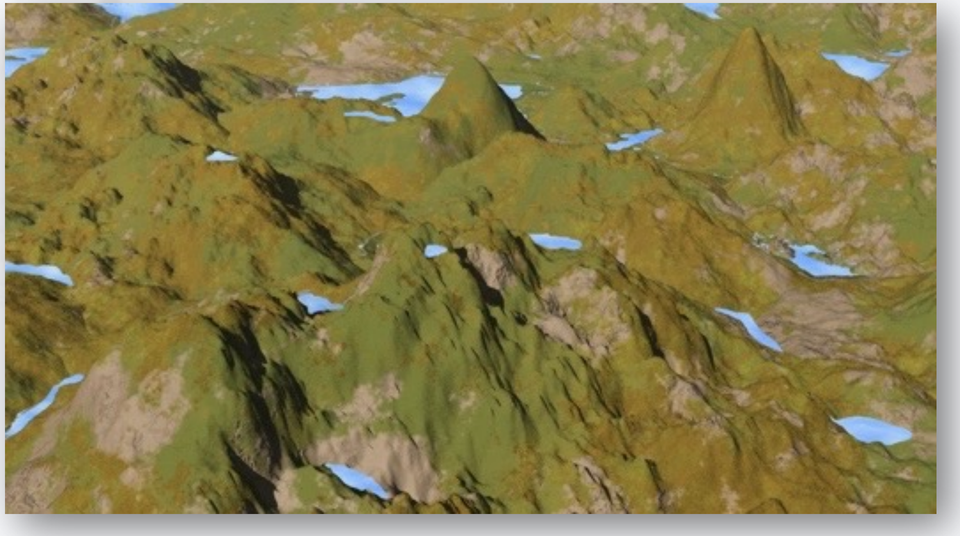
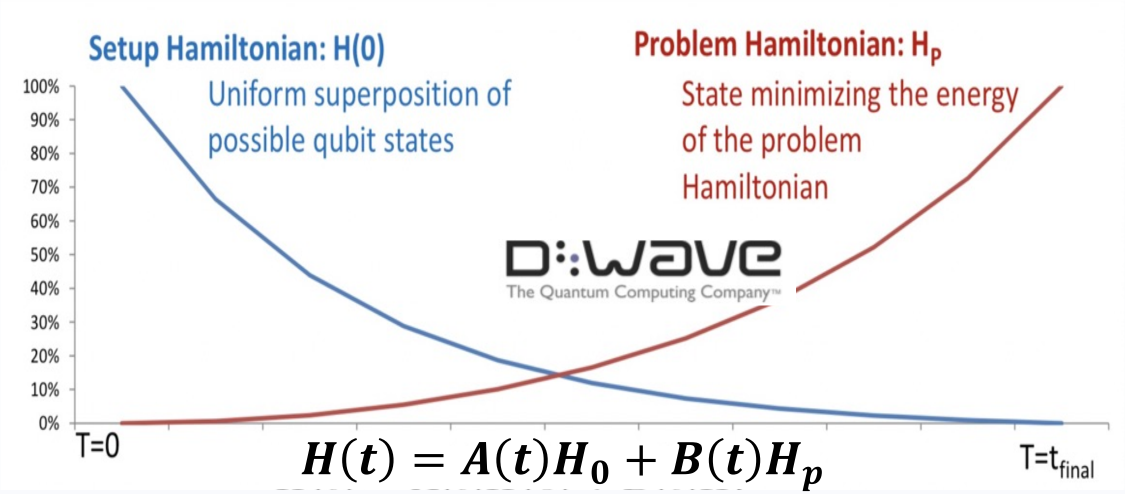


image from ISC 2021 keynote , M. Troyer

Quantum Annealing



- Annealing for optimization problems
  - Smoothly evolve probability of being at any given coordinate with time.
  - Probability increases around the coordinates of deep valleys
- Quantum systems based on **superconducting qubits**
- **D-Wave Advantage**: 5436 qubits - 15 connection (Pegasus)
  - **Quantum superposition:** scan simultaneously multiple coordinates
  - **Quantum tunneling:** reduces risk of local minima (tunnel through hills)
  - **Quantum entanglement:** discover correlations between the coordinates that lead to deep valleys.



$$H(t) = A(t)H_0 + B(t)H_p$$

T. Kadowaki and H. Nishimori, PRE, 58(5), pp. 5355-5363, (1998)
E. Farhi, et al., Science 292, 472 (2001)
W. Kaminsky, S. Lloyd, T. Orlando, arXiv:quant-ph/0403090

Today's challenges

- **Noisy Intermediate-Scale Quantum** devices
  - Limitations in terms of **stability** and **connectivity**
  - **De-coherence**, measurement errors or gate level errors
    - Specific **error mitigation techniques**
    - **Circuit optimisation**
    - Prefer algorithms **robust against noise**
- Quantum computers initially integrated in **hybrid quantum-classical infrastructure**
  - Engineering, cooling, I/O
  - Hybrid algorithms, QPU as accelerators

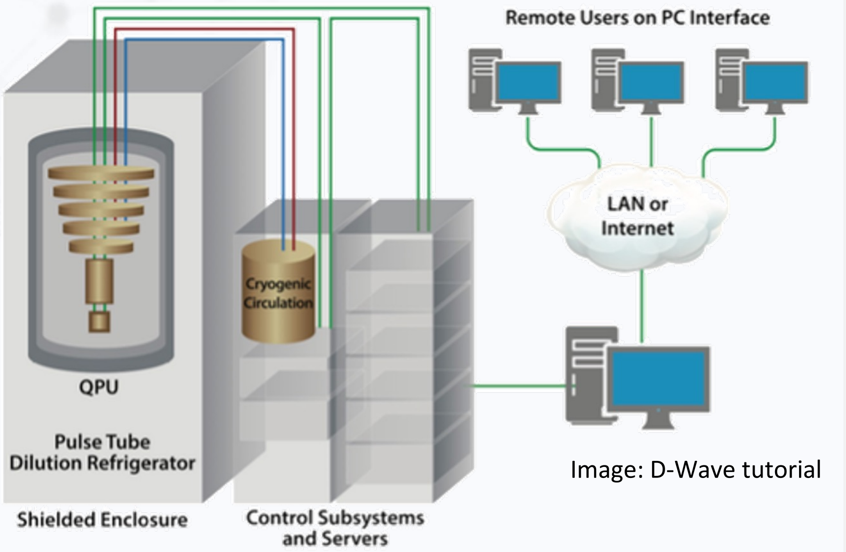
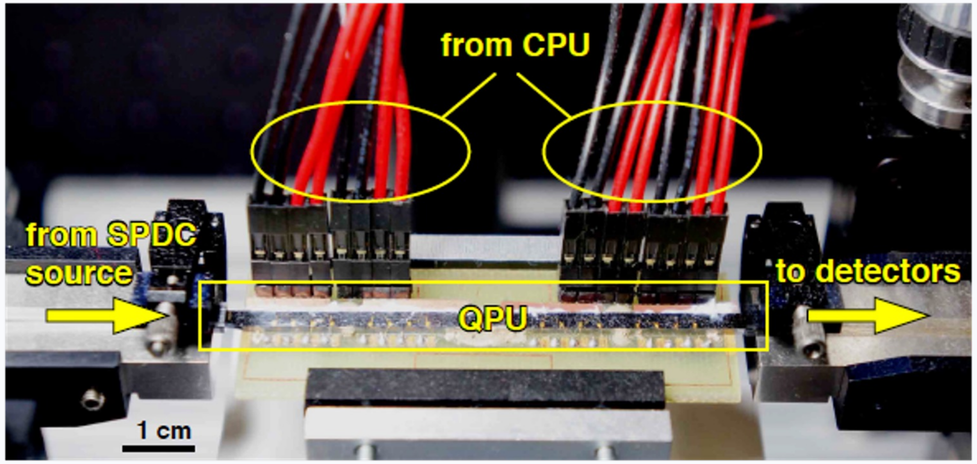


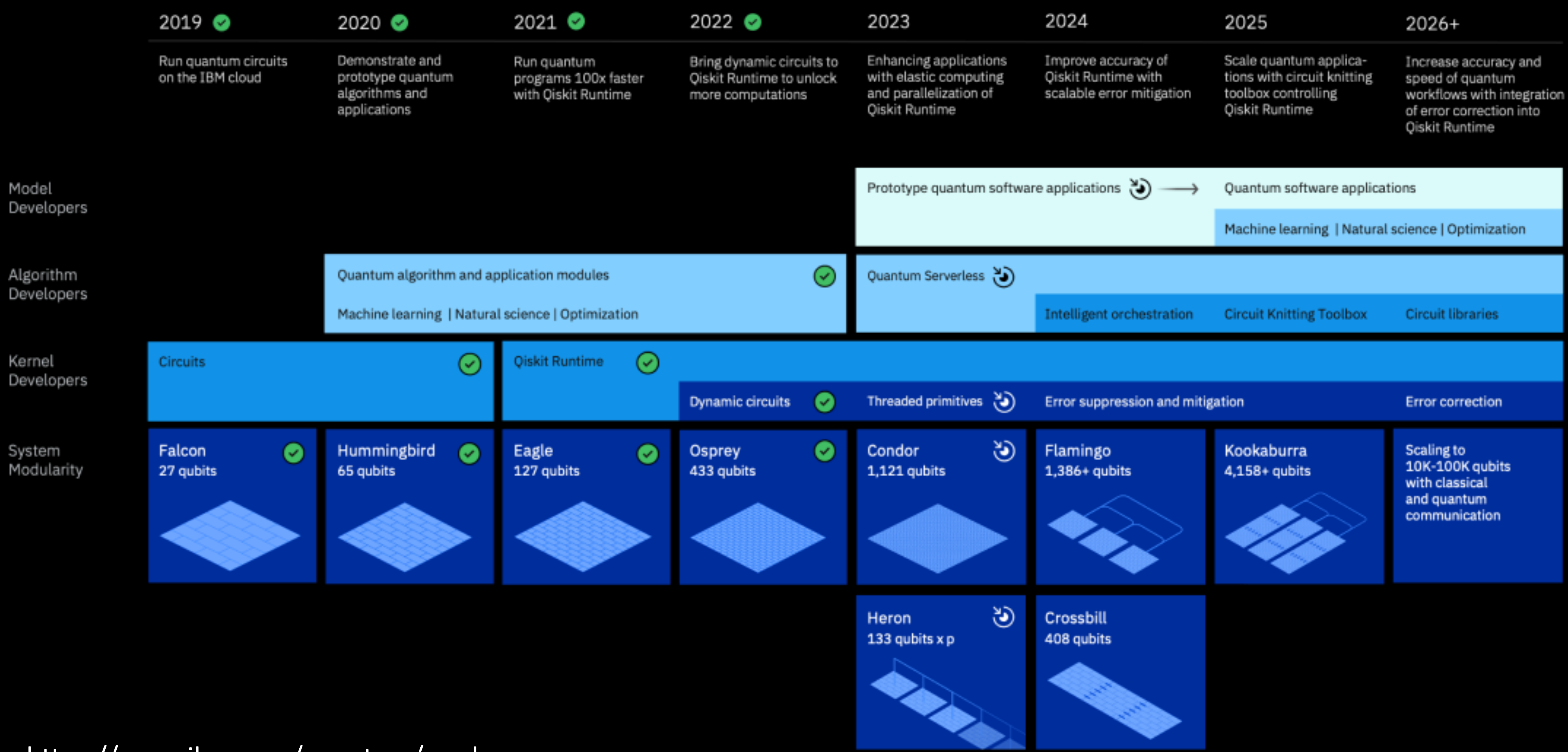
Image: D-Wave tutorial

Peruzzo, A. "**A variational eigenvalue solver on a quantum processor**." *arXiv preprint arXiv:1304.3061* (2013).



What the future brings

An example quantum roadmap from IBM



	2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023	2024	2025	2026+
	Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime
Model Developers					Prototype quantum software applications →		Quantum software applications Machine learning | Natural science | Optimization	
Algorithm Developers		Quantum algorithm and application modules ✓ Machine learning | Natural science | Optimization			Quantum Serverless	Intelligent orchestration	Circuit Knitting Toolbox	Circuit libraries
Kernel Developers	Circuits ✓		Qiskit Runtime ✓	Dynamic circuits ✓	Threaded primitives	Error suppression and mitigation		Error correction
System Modularity	Falcon 27 qubits ✓	Hummingbird 65 qubits ✓	Eagle 127 qubits ✓	Osprey 433 qubits ✓	Condor 1,121 qubits	Flamingo 1,386+ qubits	Kookaburra 4,158+ qubits	Scaling to 10K-100K qubits with classical and quantum communication
					Heron 133 qubits x p	Crossbill 408 qubits		

https://www.ibm.com/quantum/roadmap

- How do we define advantage?
  - Speed-up and complexity
  - Sample efficiency
  - Representational power
  - Energy efficiency???

- Evaluate performance on realistic use cases

The CERN Quantum Technology Initiative:

Understanding the impact of quantum technologies in HEP

The CERN QTI launched in 2020

Voir en *français*

CERN meets quantum technology

The CERN Quantum Technology Initiative will explore the potential of devices harnessing perplexing quantum phenomena such as entanglement to enrich and expand its challenging research programme

30 SEPTEMBER, 2020 | By Matthew Chalmers

The AEgIS 1T antimatter trap stack. CERN's AEgIS experiment is able to explore the multi-particle entangled nature of photons from positronium annihilation, and is one of several examples of existing CERN research with relevance to quantum technologies. (Image: CERN)

Quantum simulation and HEP theory applications

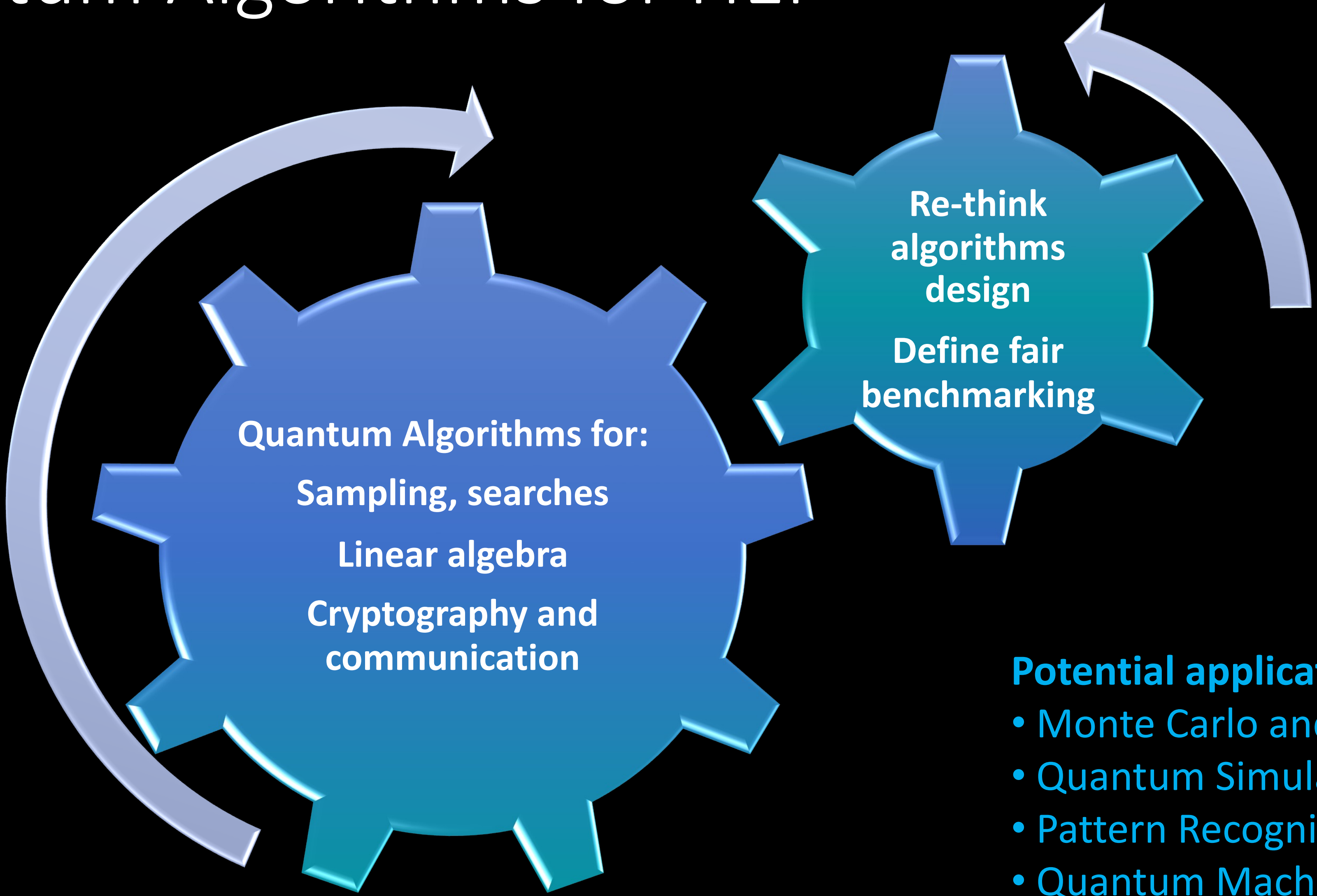
Quantum Computing

Quantum Sensing

Quantum Communication

QTI Roadmap: https://doi.org/10.5281/zenodo.5553774

Quantum Algorithms for HEP



Quantum Algorithms for:

Sampling, searches

Linear algebra

Cryptography and communication

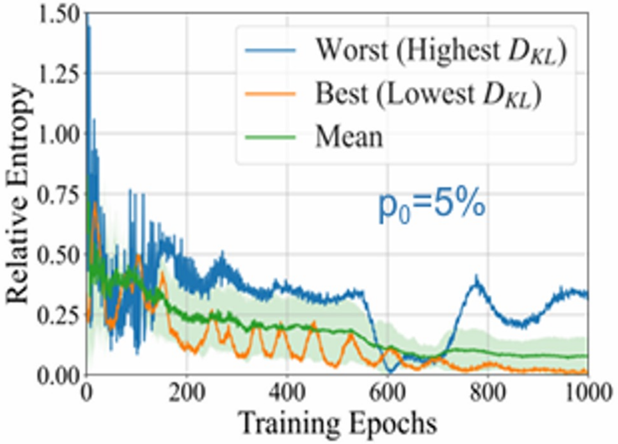
Re-think algorithms design

Define fair benchmarking

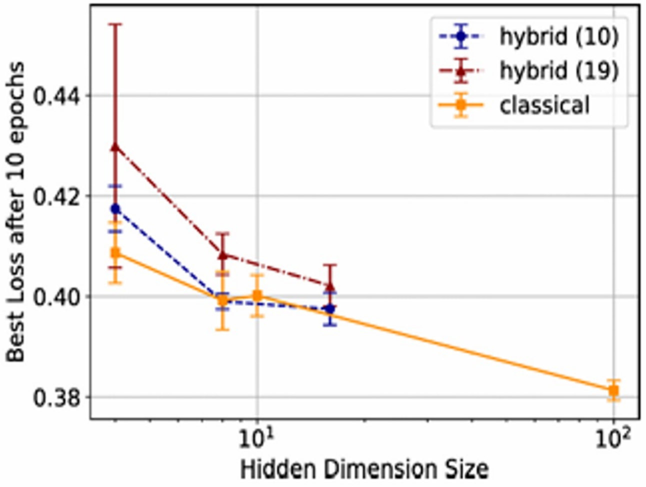
Potential applications:
- Monte Carlo and Event Generation
- Quantum Simulation
- Pattern Recognition
- Quantum Machine Learning

QC @CERN

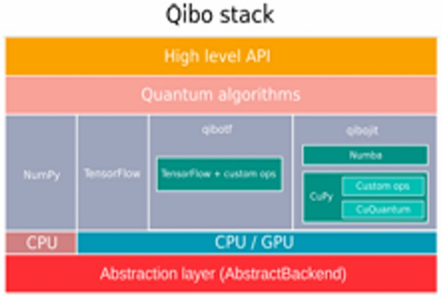
Borras, Kerstin, et al. "**Impact of quantum noise on the training of quantum Generative Adversarial Networks**." *arXiv preprint arXiv:2203.01007* (2022).

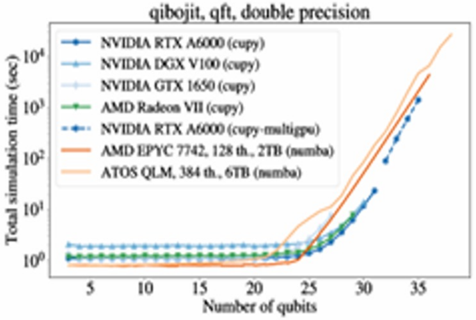


Tüysüz, Cenk, et al. "**Hybrid quantum classical graph neural networks for particle track reconstruction.**" *Quantum Machine Intelligence* 3.2 (2021): 1-20.

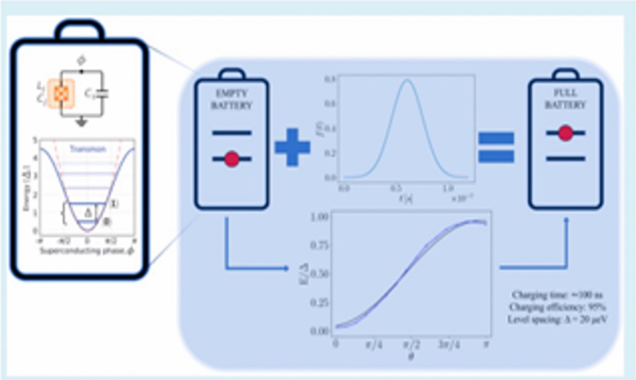


E.Stavros et all., **Quantum simulation with just-in-time compilation**, Quantum 2022

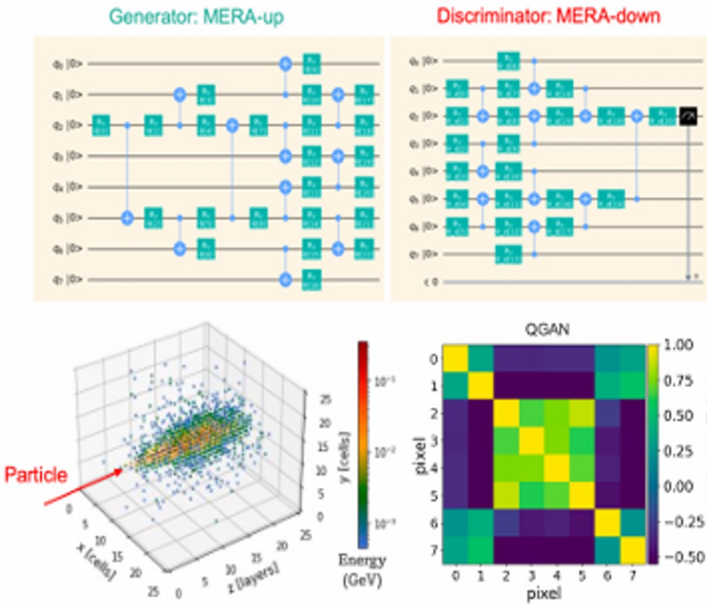




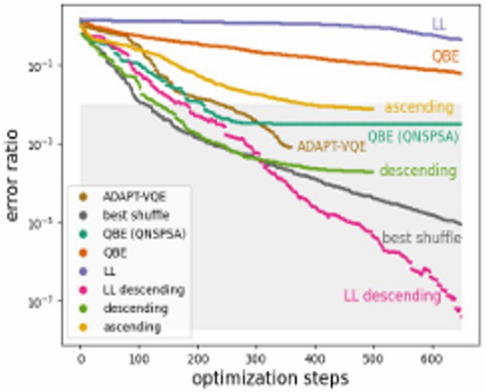
G. Gemme, M. Grossi et al, **IBM Quantum Platforms: A Quantum Battery Perspective**, *Batteries 8, 43 (2022)*



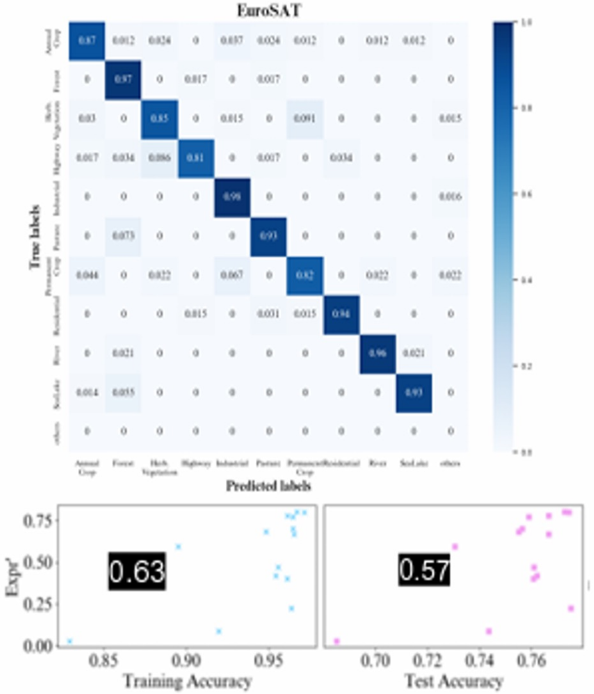
F.Rehm, **Full Quantum GAN Model for HEP Detector Simulations**, ACAT22



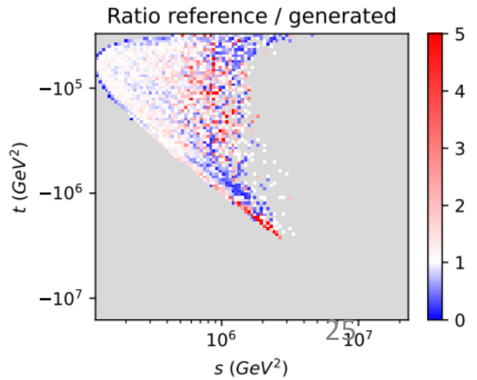
O. Kiss, **Quantum computing of the 6Li nucleus via ordered unitary coupled cluster**, 10.1103/PhysRevC.106.034325



S.Chang, et all, **Hybrid Quantum-Classical Networks for Reconstruction and Classification of Earth Observation Images**, ACAT22



Bravo-Prieto, Carlos, et al. "**Style-based quantum generative adversarial networks for Monte Carlo events.**" *Quantum 2022*

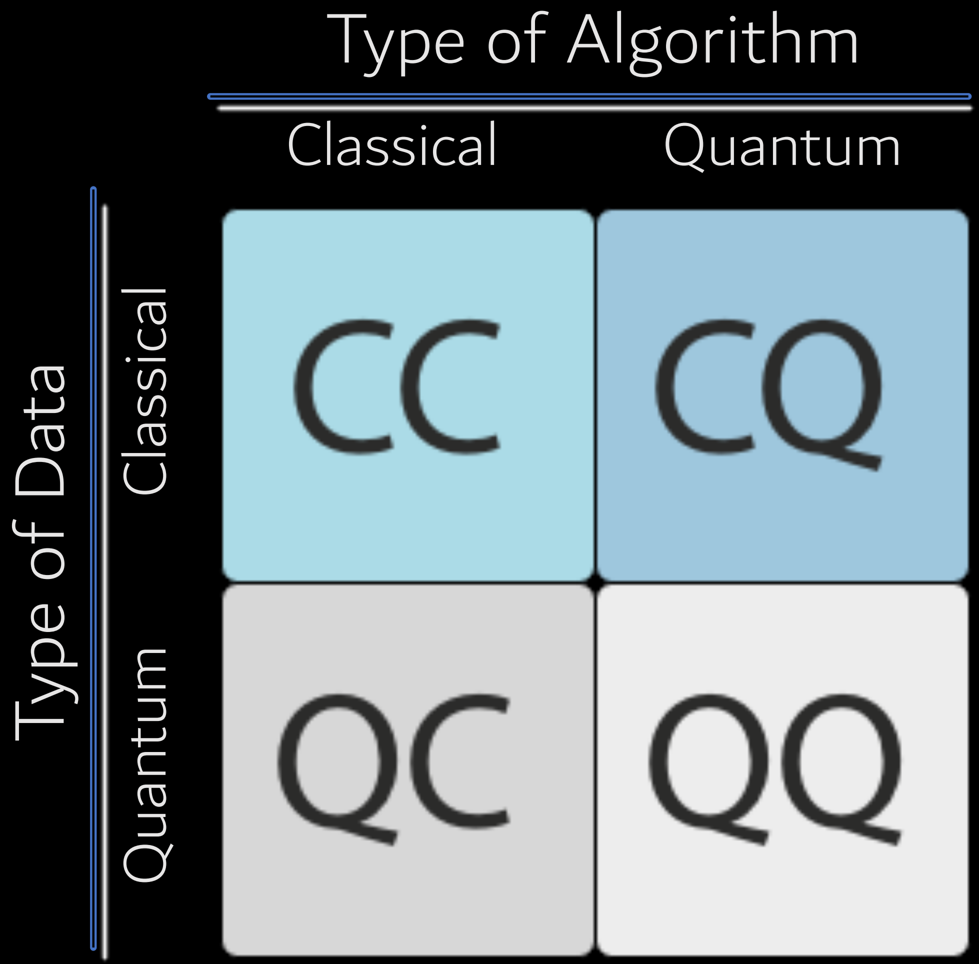


Quantum Machine Learning :

Some basic concepts

QML in HEP

- Does it make sense to use QML in HEP?
- How do we understand when it is *useful* ?
- Which are the QML models we can leverage?



		Type of Algorithm	
		Classical	Quantum
Type of Data	Classical	CC	CQ
	Quantum	QC	QQ

Classical Intractability:

- No established recipe for classical data
- Compromise between algorithm **expressivity** vs **trainability** and **generalization**

(Quantum) ML Lifecycle

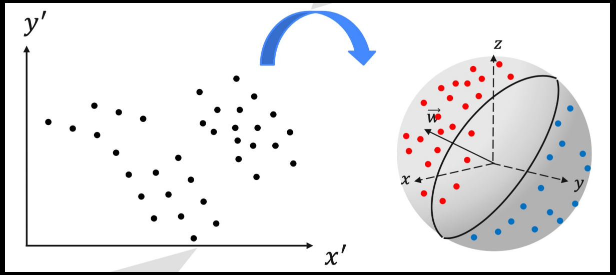
Data Preparation

Model Definition

Model Training

Model Testing

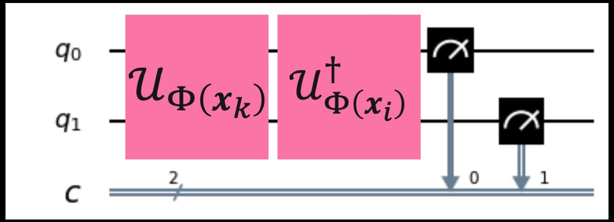
Model Interpretation



Data Embedding

Adapt classical learning models to quantum space

Readout and measurement "shots"



The advantage of many known QML algorithms is impeded today by I/O bottleneck

Models

Variational algorithms (ex. QNN)

Gradient-free or **gradient-based** optimization

Data Embedding can be **learned**

Ansatz design can leverage data symmetries[1]

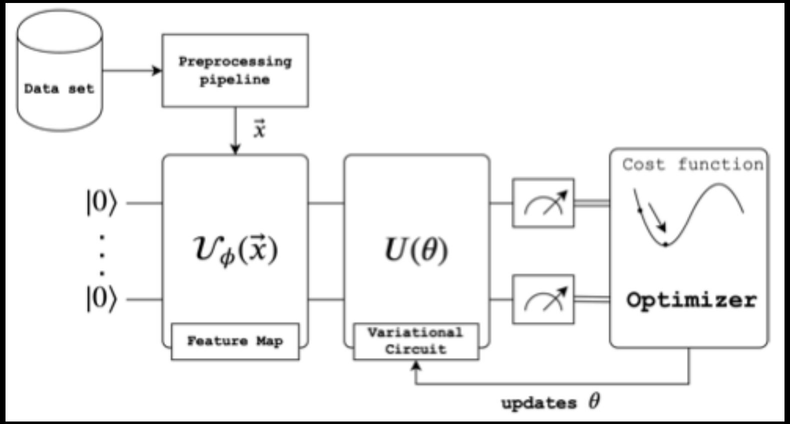


Image credit SwissQuantumHub

Representer theorem:

Implicit models achieve **better accuracy**[3]

Explicit models exhibit **better generalization** performance

Kernel methods (ex. QSVM)

Feature maps as **quantum kernels**

Classical **kernel-based training** (**convex** losses)

Identify classes of kernels that relate to specific data **structures**[2]

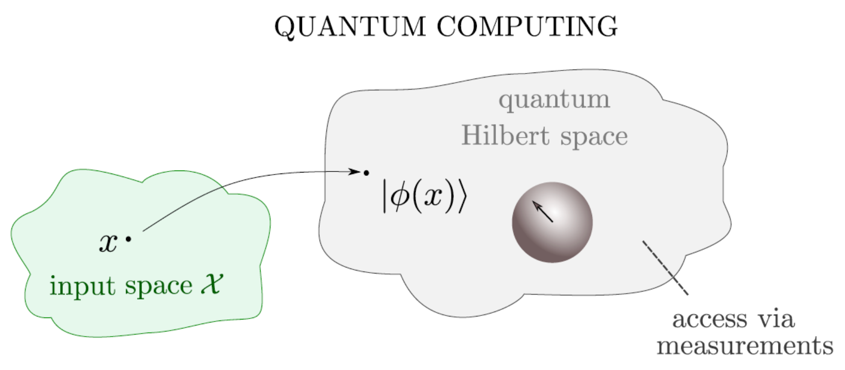


Image credit M. Schuld

Energy-based ML (ex. QBM)

Build network of stochastic binary units and optimise their energy.

QBM has quadratic energy function that follows the Boltzman distribution (Ising Hamiltonian)

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[1] Bogatskiy, Alexander, et al. "**Lorentz group equivariant neural network for particle physics**." PMLR, 2020.

[2] Glick, Jennifer R., et al. "**Covariant quantum kernels for data with group structure**." *arXiv:2105.03406* (2021).

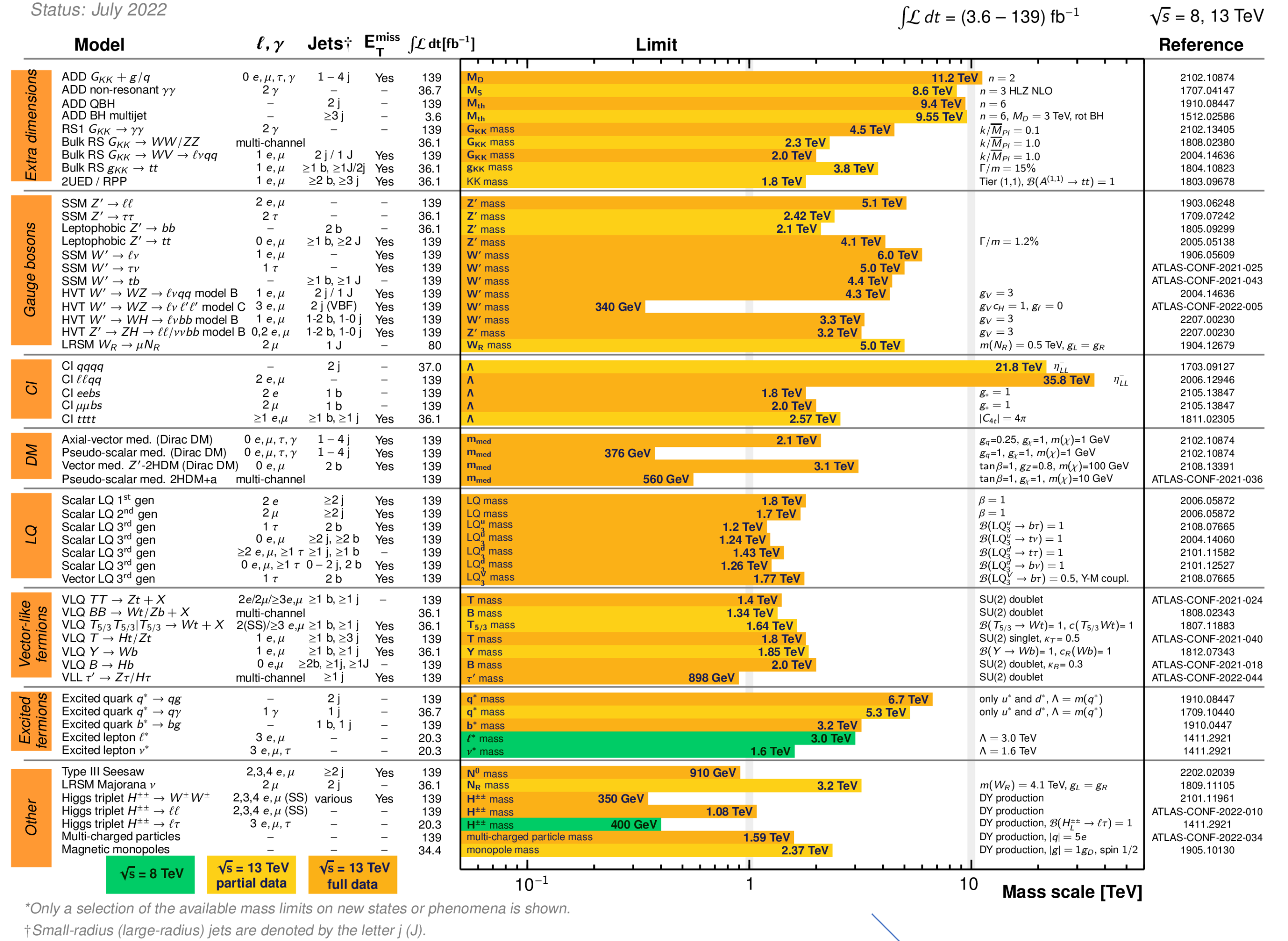
[3] Jerbi, Sofiene, et al. "**Quantum machine learning beyond kernel methods**." *arXiv preprint arXiv:2110.13162* (2021).

Quantum Machine Learning examples:

Anomaly Detection

New Physics at the LHC

So far only **negative results** in **direct** (model dependent) searches



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits
Status: July 2022

ATLAS Preliminary
$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$
$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D	11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th}	9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass	2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e, μ	1-2 b, 1-0 j	Yes	139	W' mass	3.3 TeV	$g_V = 3$	2207.00230
	HVT $Z' \to ZH \to \ell\ell/\nu\nu bb$ model B	0,2 e, μ	1-2 b, 1-0 j	Yes	139	Z' mass	3.2 TeV	$g_V = 3$	2207.00230
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ	35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ	1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ	2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med}	2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	m_{med}	3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med}	560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass	1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass	1.2 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^V mass	1.77 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass	1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass	898 GeV	SU(2) doublet	ATLAS-CONF-2022-044
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass	3.2 TeV		1910.0447
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass	910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass	1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	139	multi-charged particle mass	1.59 TeV	DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

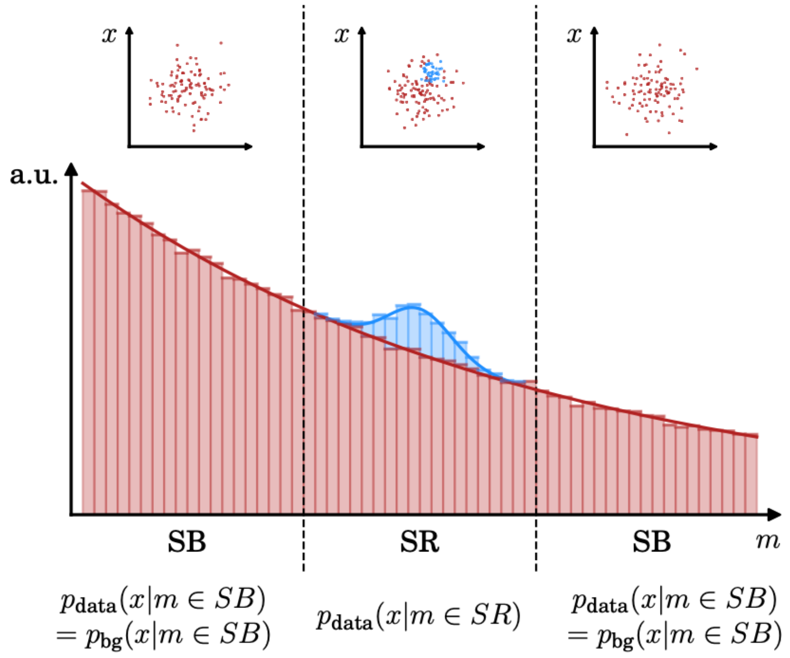
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

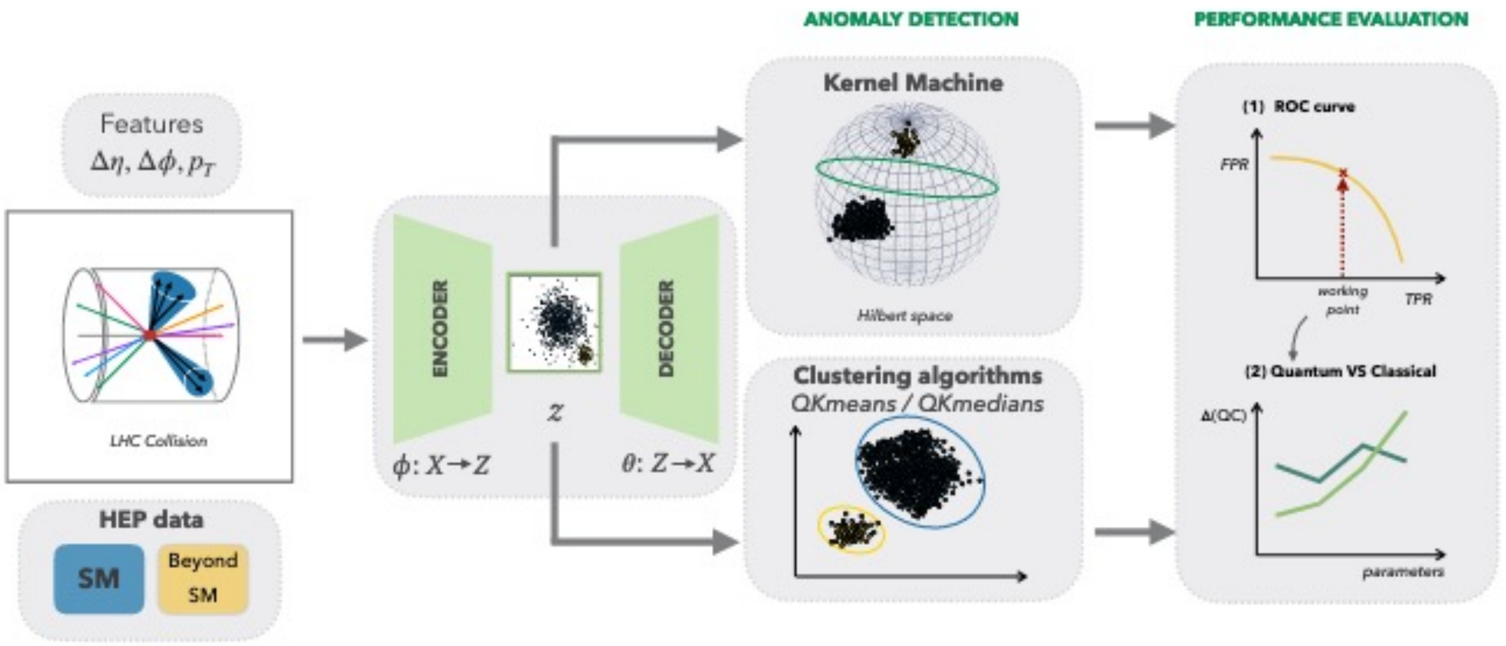
How to insure we do not miss potential discoveries?

We can design model agnostic searches!

Unsupervised learning for Anomaly Detection

Anomaly detection can point to new physics at the LHC





Standard Model jets

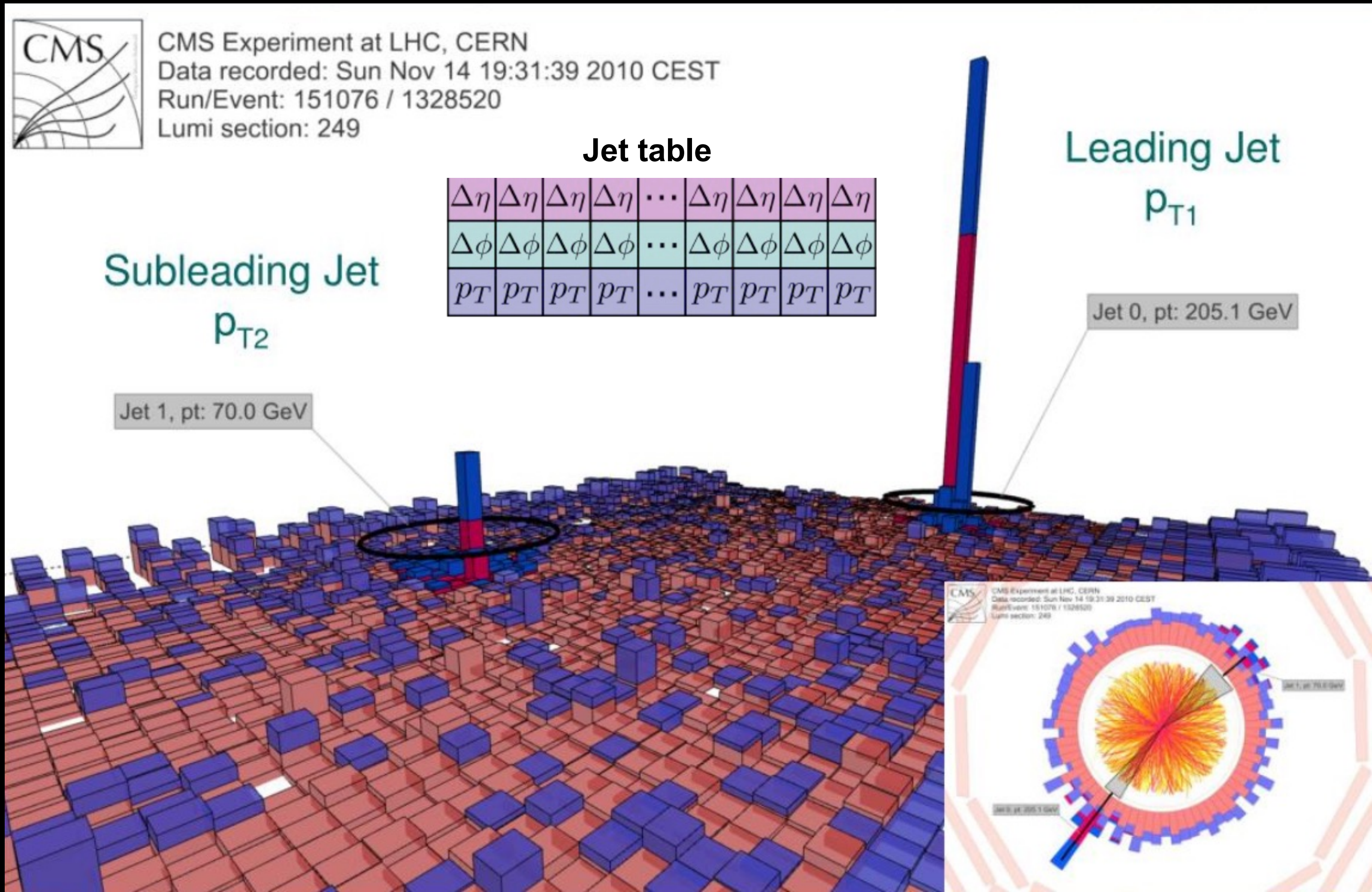
Simulate QCD multi-jets at the LHC

Build jet from 100 highest pt particles

Apply realistic event selection

Convolutional AutoEncoder
learns the jet **internal structure**

$$\mathbb{R}^{300} \to \mathbb{R}^{\ell} , \ell = 4, 8,16$$



Jet table

$\Delta\eta$	$\Delta\eta$	$\Delta\eta$	$\Delta\eta$	$\cdots$	$\Delta\eta$	$\Delta\eta$	$\Delta\eta$	$\Delta\eta$
$\Delta\phi$	$\Delta\phi$	$\Delta\phi$	$\Delta\phi$	$\cdots$	$\Delta\phi$	$\Delta\phi$	$\Delta\phi$	$\Delta\phi$
p_T	p_T	p_T	p_T	$\cdots$	p_T	p_T	p_T	p_T

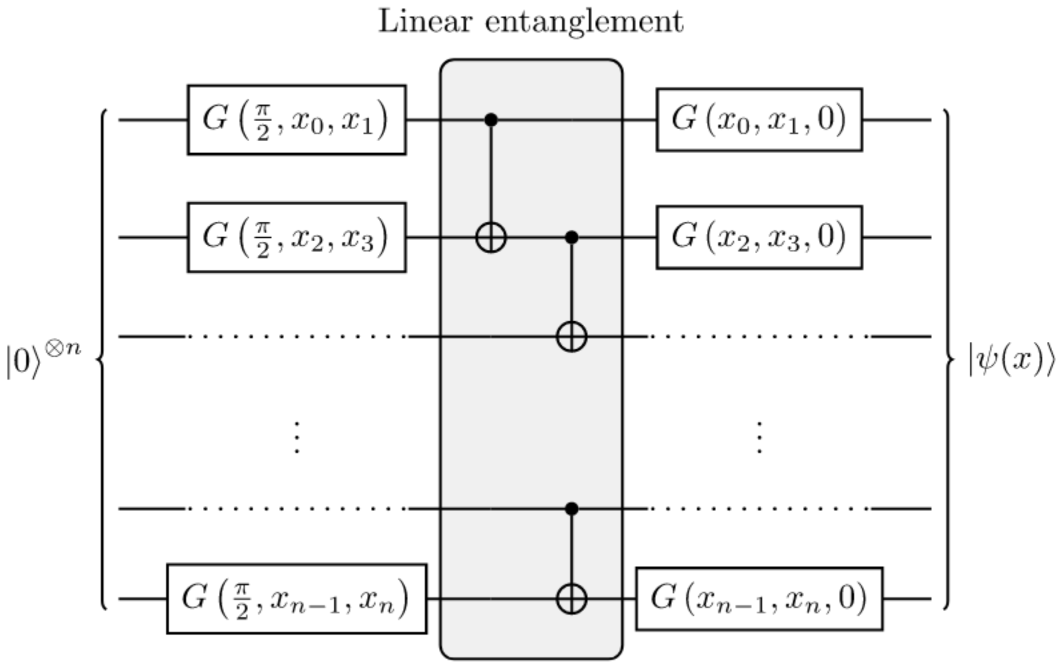
Unsupervised kernel machine

Find the hyperplane that maximizes the distance of the data from the origin of the feature vector space

Upper bound on fraction of anomalies in training data at 0.01 (at most 1% QCD training data are falsely flagged)

$$k(x_i, x_j) := \mathrm{tr}[\rho(x_i)\rho(x_j)] = \left|\langle 0|U^\dagger(x_i)U(x_j)|0\rangle\right|^2$$

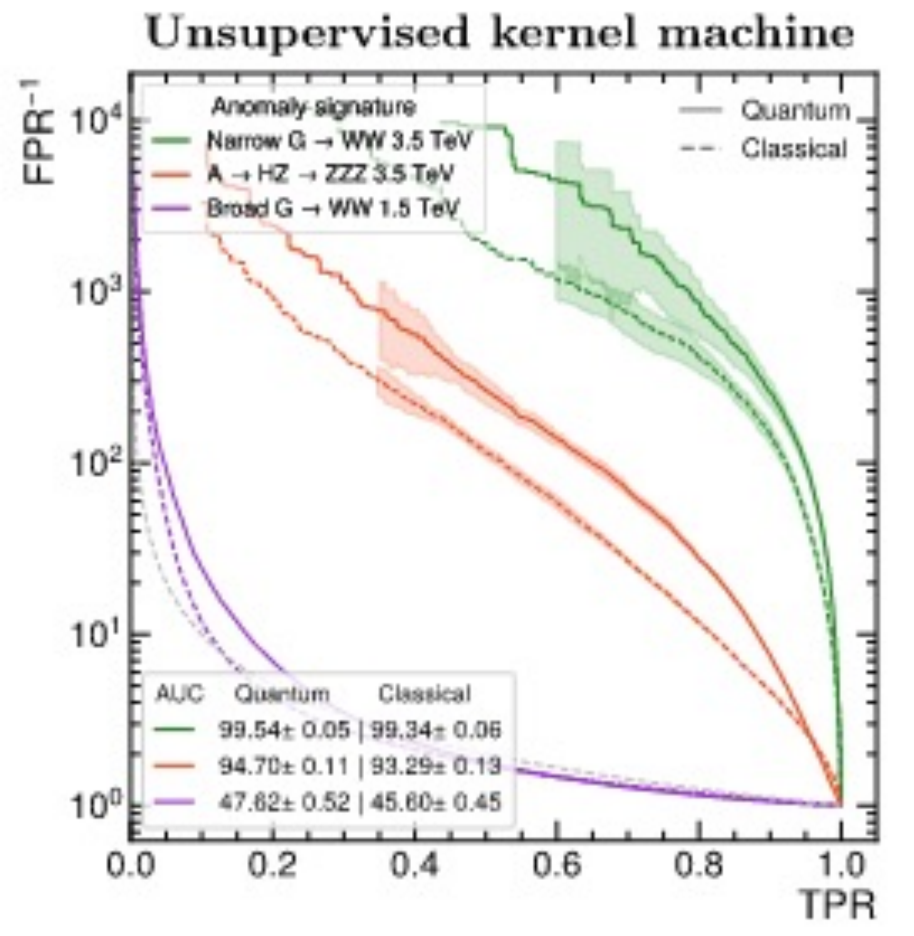
$$\rho(x_i) := U(x_i)\,|0\rangle\,\langle 0|\,U^\dagger(x_i)$$



$$\min_{w\in\mathcal{F},\,\xi\in\mathbb{R}^\ell,\,\rho\in\mathbb{R}} \quad \frac{1}{2}||w||^2 + \frac{1}{\nu\ell}\sum_i \xi_i - \rho$$

$$\text{subject to} \quad w \cdot \Phi(x_i) \geq \rho - \xi_i,\ \xi_i \geq 0,\ \forall i \quad \nu \in (0,1)$$

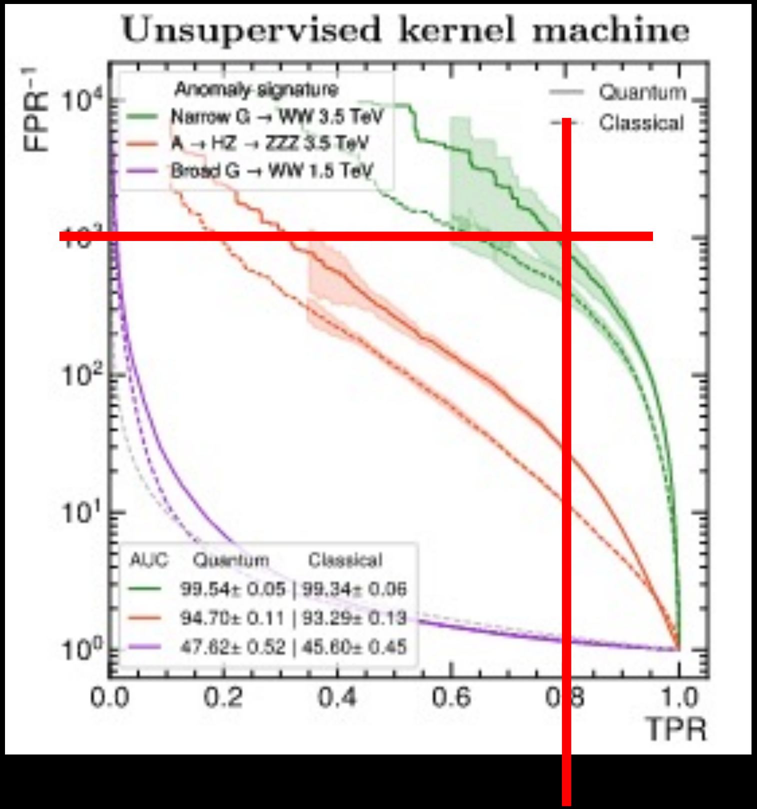
Results



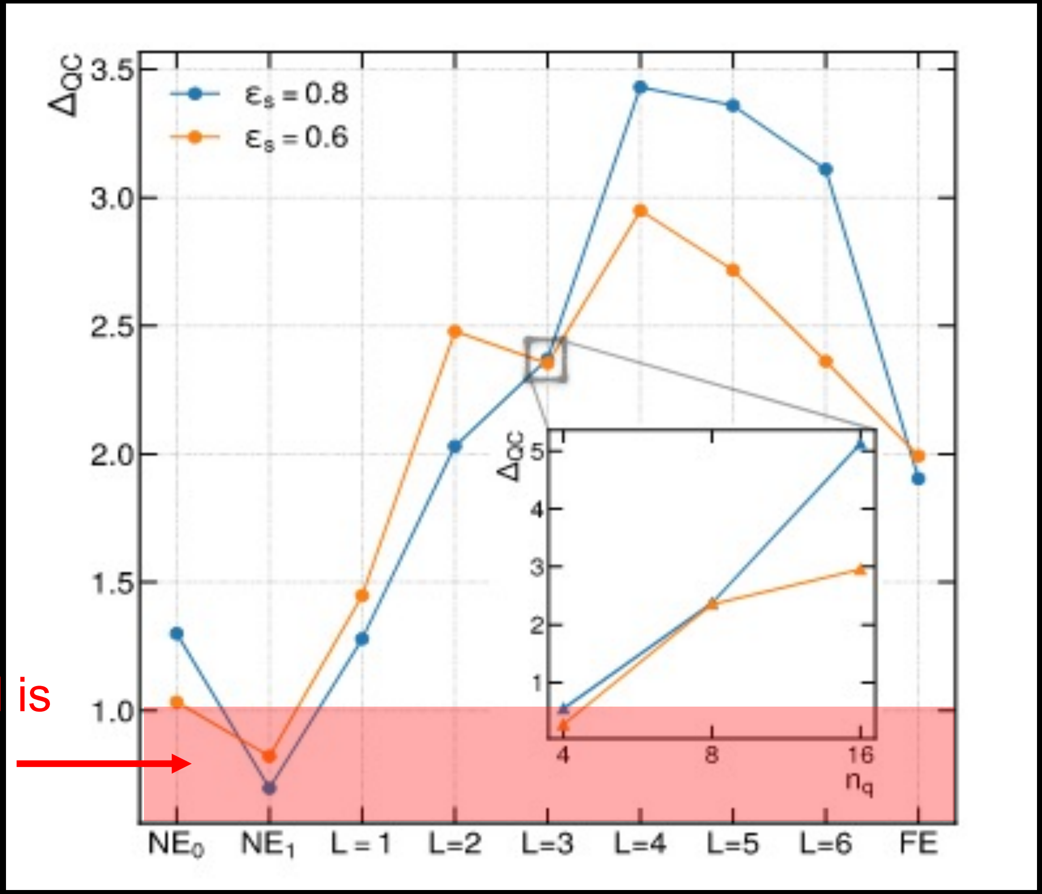
Is this an «advantage» we can use?

Quantum anomaly detection in the latent space of proton collision events at the LHC
Vasileios Belis *et al.*, *arXiv:2301.10780*.

In reality....



Classical is better



Higher is better

Increasing entanglement & expressivity

Quantum anomaly detection in the latent space of proton collision events at the LHC
Vasileios Belis *et al.*, *arXiv:2301.10780*.

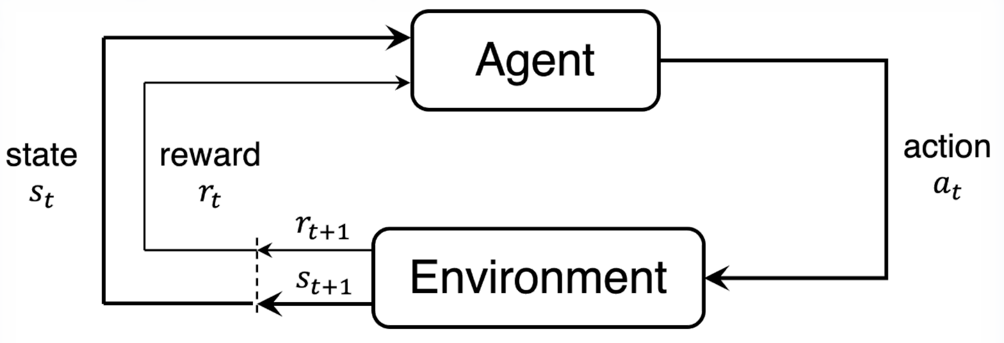
Quantum Machine Learning examples:

Reinforcement Learning

Schenk, M *et al.* Hybrid actor-critic algorithm for quantum reinforcement learning at CERN beam lines. *arXiv preprint arXiv:2209.11044.*, CHEP2023

Reinforcement learning

... in a nutshell



RL book: Sutton & Barto

Trial-and-error learning

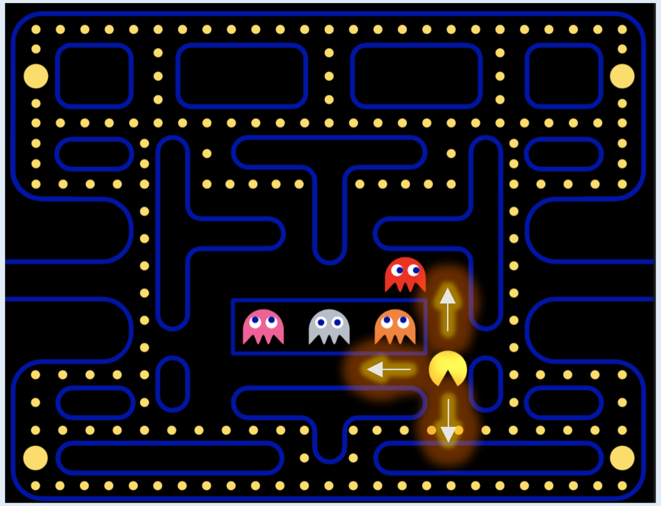
- Agent **takes actions** in environment and **collects rewards**

Q-learning

- Estimate **return using Q-function** $Q(\mathbf{s},\mathbf{a})$
- **Learn iteratively** using **collected interactions**
- Once trained, **select action greedily**

$$a = \arg\max_{\mathrm{a}} Q(\boldsymbol{s},\boldsymbol{a})$$

Example: Pacman



State
where am I? Where are ghosts, snacks, cookies?

Actions
up, down, left, right

Reward
food (+), ghosts (-)

Return
how much food am I going to eat over time

Free-energy based RL (FERL)

RL performance depends **on type of Q-function approximator**

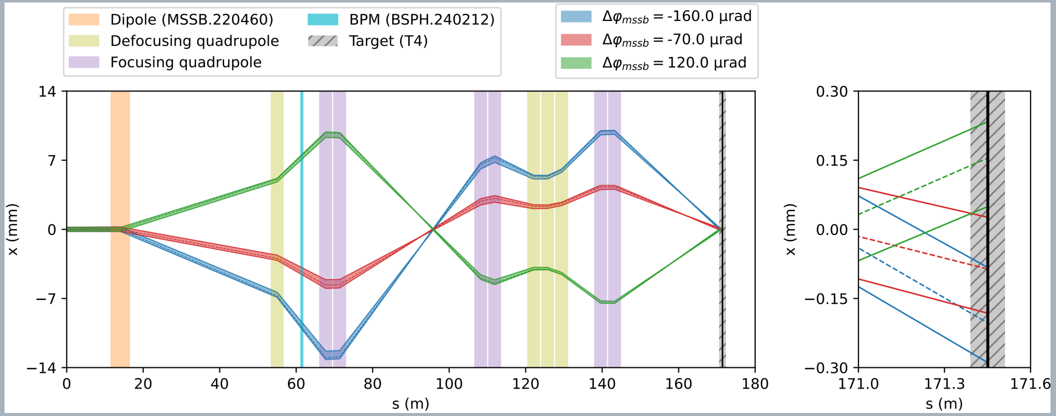
- **Classical Deep Q-learning (DQN)**
  Feed-forward neural net
- **Free-energy based RL (FERL)**
  Quantum Boltzmann machine (QBM)

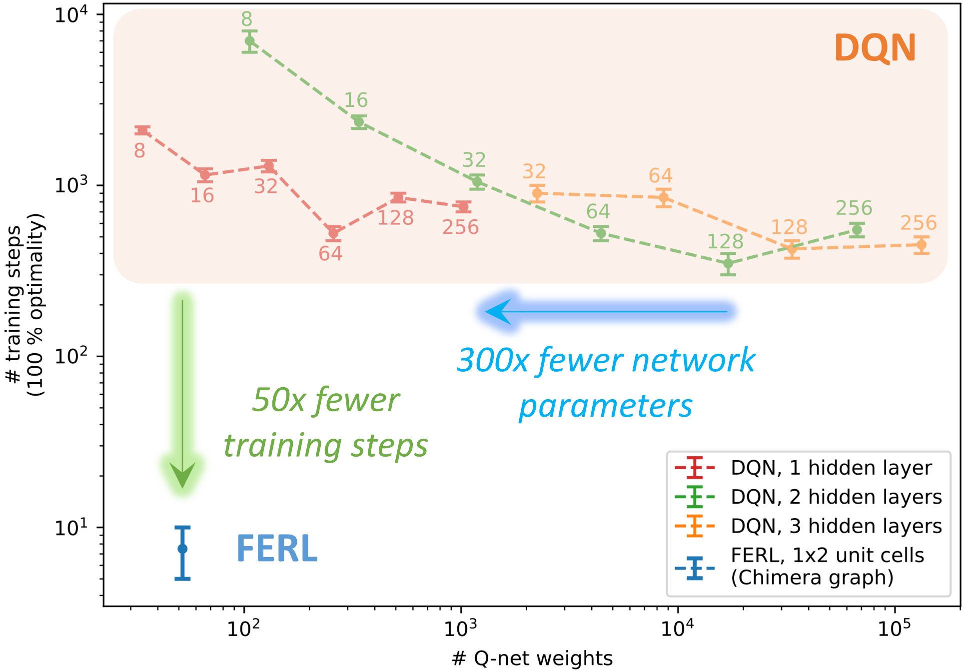
Key concept: sample-efficiency

- Relevant for **particle accelerator control** given cost of beam time *(online training)*

1st study: 1D beam steering

CERN *North Area transfer line (discrete action space)*





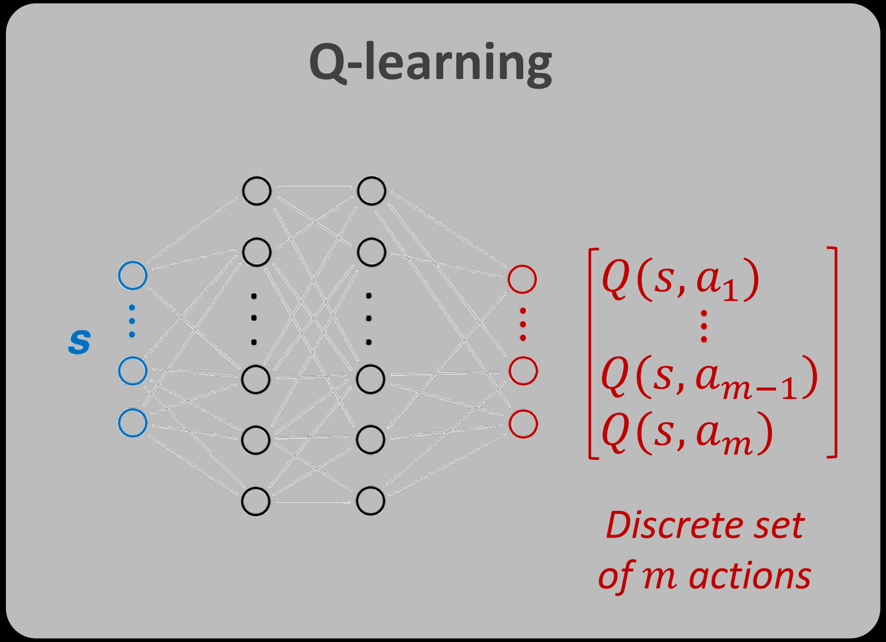
50x fewer training steps

300x fewer network parameters

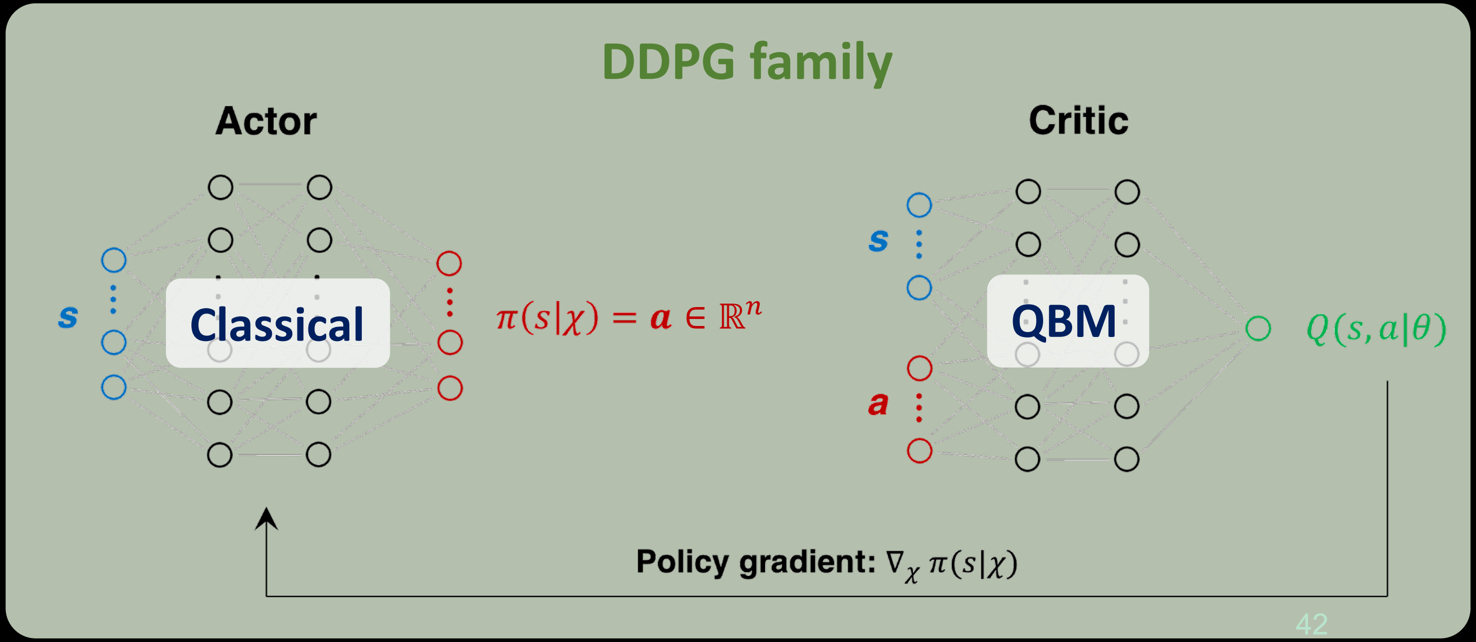
Developing a hybrid actor-critic scheme

Accelerator optimization requires **continuous action space** ➡ **develop hybrid actor-critic algorithm**

- **QBM replaces classical critic net**



Q-learning



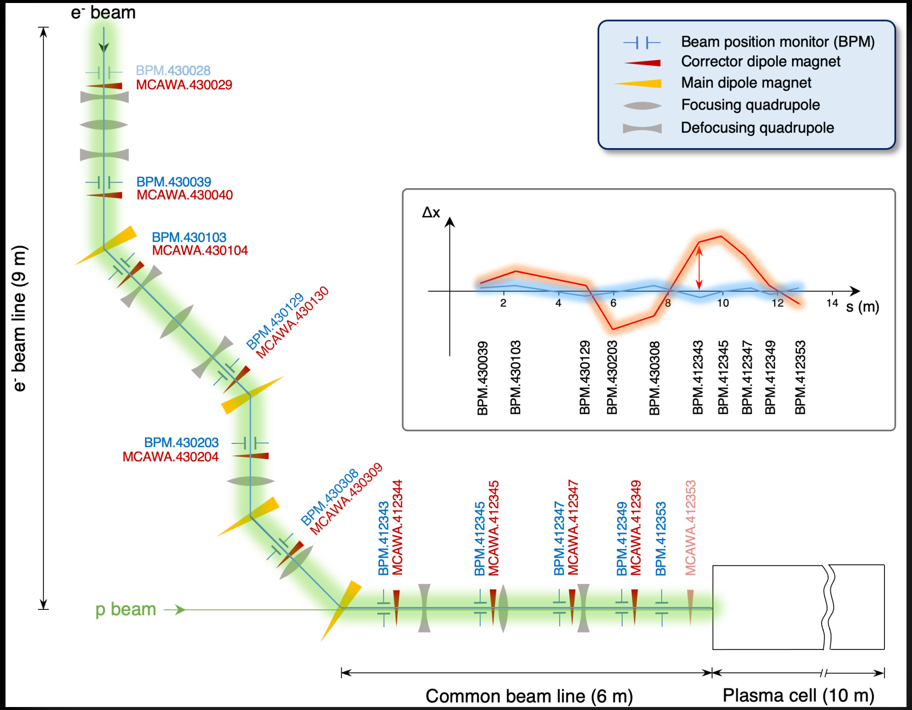
DDPG family

2nd study: 10D continuous beam steering

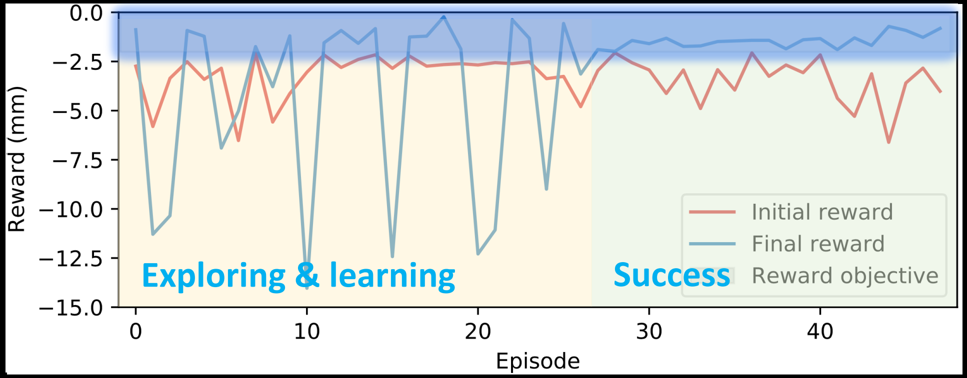
Environment: e⁻ beam line of AWAKE

- **Action:** deflection angles at 10 correctors
- **State:** beam positions at 10 BPMs
- **Objective:** minimize beam trajectory rms
  - ⇨ **reward:** negative rms from 10 BPMs

***AWAKE:** Advanced Proton Driven Plasma Wakefield Acceleration Experiment*



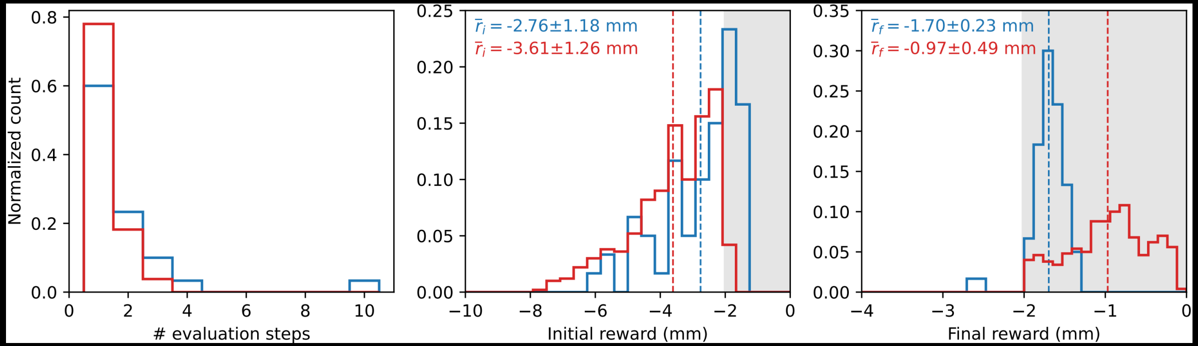
Training: on D-Wave Advantage quantum annealer (QA)



Objective

Evaluation: on actual beam line

Real vs. simulated QA



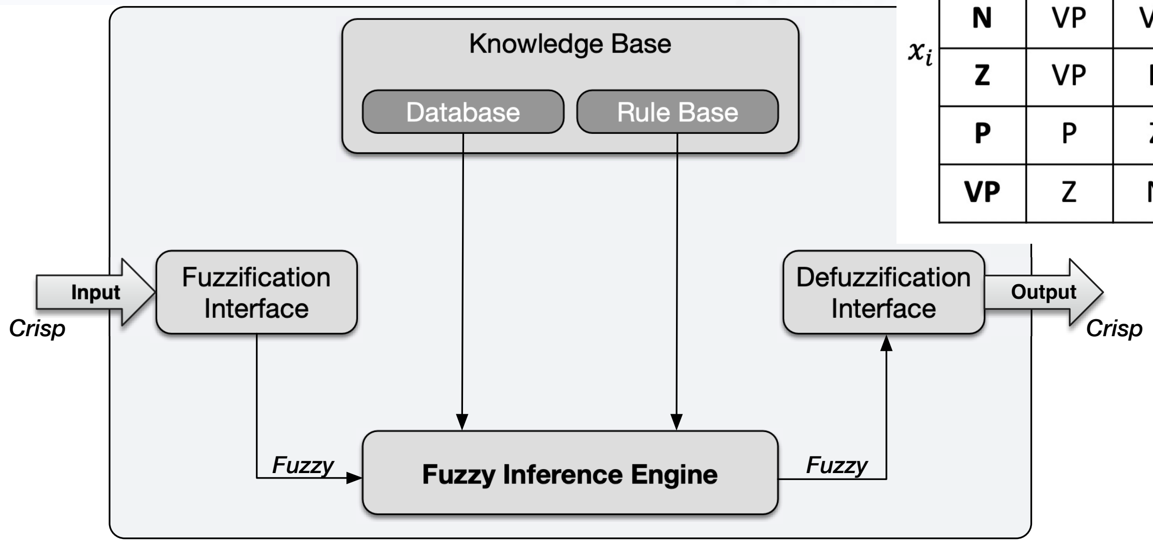
- Agent minimizes rms in **1 step in 60 % cases**
- **Hyperparameter** tuning with **simulated** QA

1-slide excursion: quantum fuzzy logic controller

- **Alternative control algorithm** to RL
- **Fuzzy Logic** is used to develop control systems **based on linguistic rules** ⇨ **highly interpretable**
- **Quantum Fuzzy Control System** *(G. Acampora, R. Schiattarella, A. Vitiello)*
  Exploit **exponential advantage** in computing fuzzy rules on quantum computers
- **Successfully evaluated on AWAKE beam line, no training required**

Evaluation: on AWAKE beam line

Objective reached typically in 1 step



Knowledge Base

Database

Rule Base

Input

Crisp

Fuzzification Interface

Fuzzy

Fuzzy Inference Engine

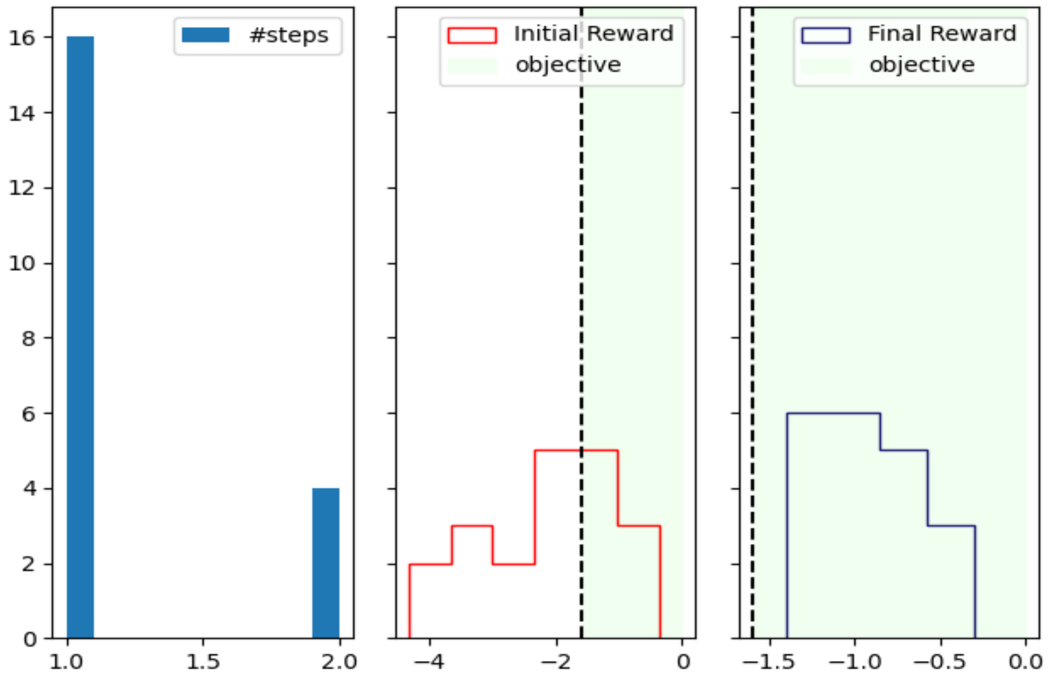
Fuzzy

Defuzzification Interface

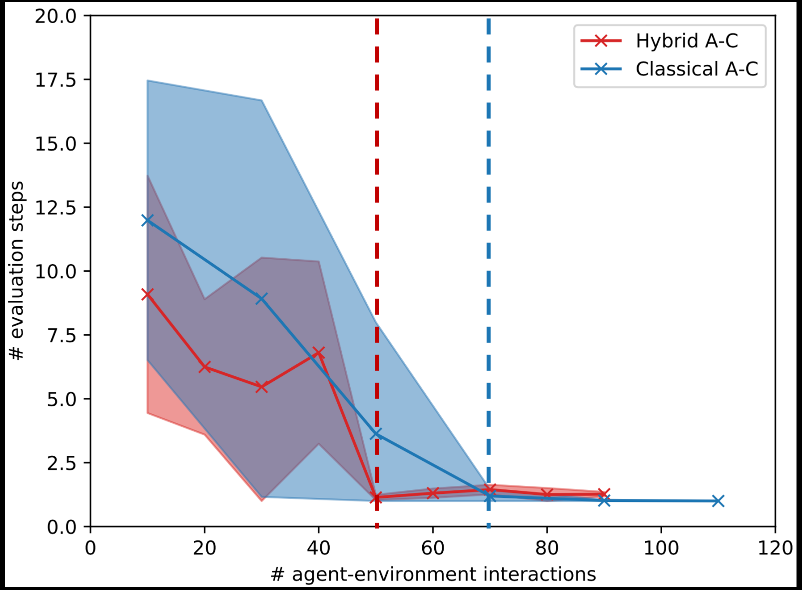
Output

Crisp

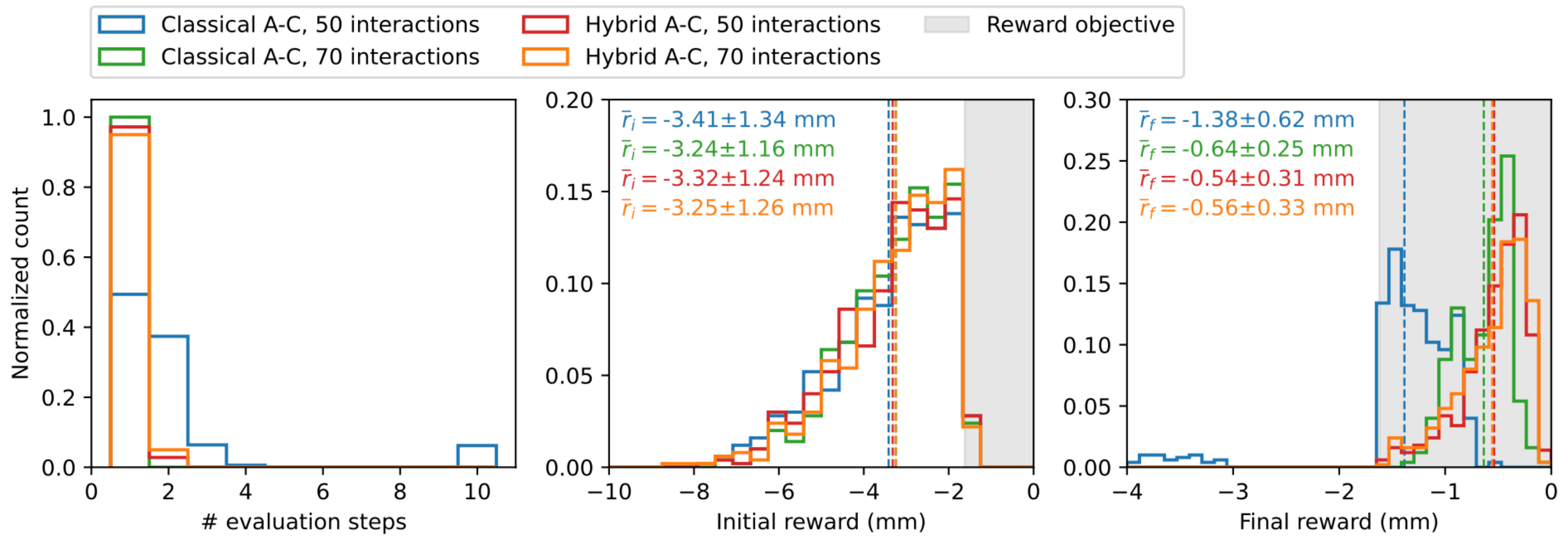
		dk_i				
		VN	**N**	**Z**	**P**	**VP**
x_i	**VN**	VP	VP	VP	P	Z
	N	VP	VP	P	Z	N
	Z	VP	P	Z	N	VN
	P	P	Z	N	VN	VN
	VP	Z	N	VN	VN	VN



2nd study: 10D continuous beam steering

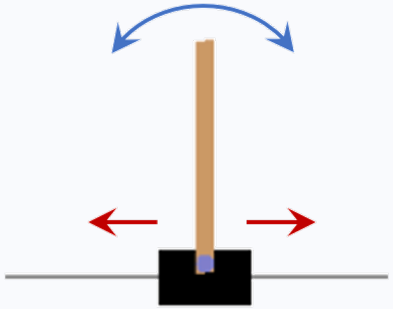


- **Hybrid actor-critic (A-C) works**
- **Minor improvement in terms of sample efficiency**
  50 vs 70 interactions
- **Very few interactions sufficient** for both approaches
- **Dynamics potentially too simple** (linear)
  ⇨ Move towards **more complex RL benchmarks**



3rd study: Cartpole-v1

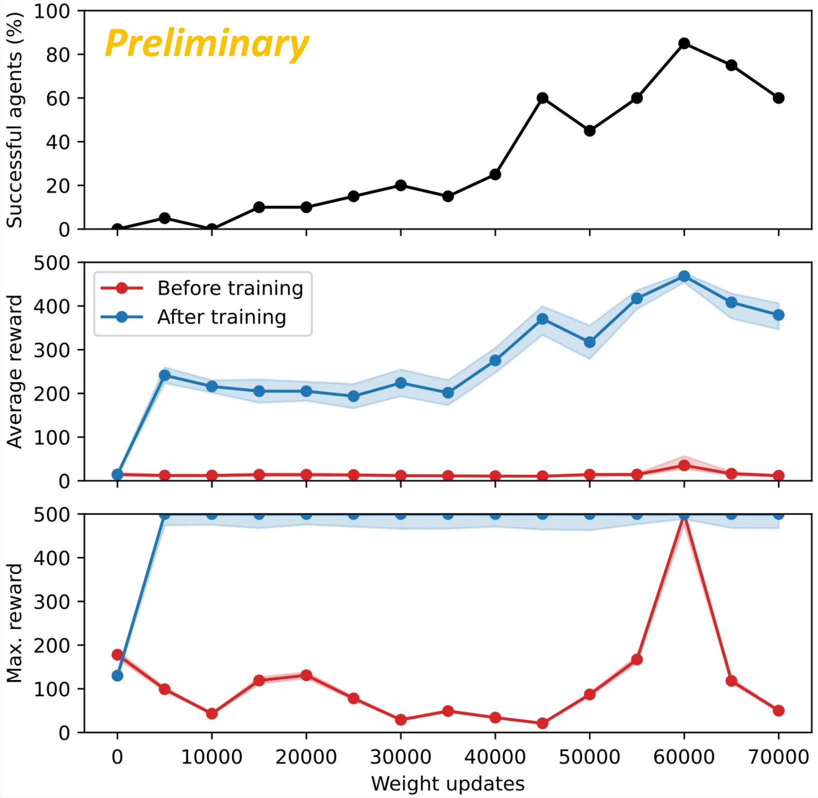
Discrete action problem, non-linear dynamics



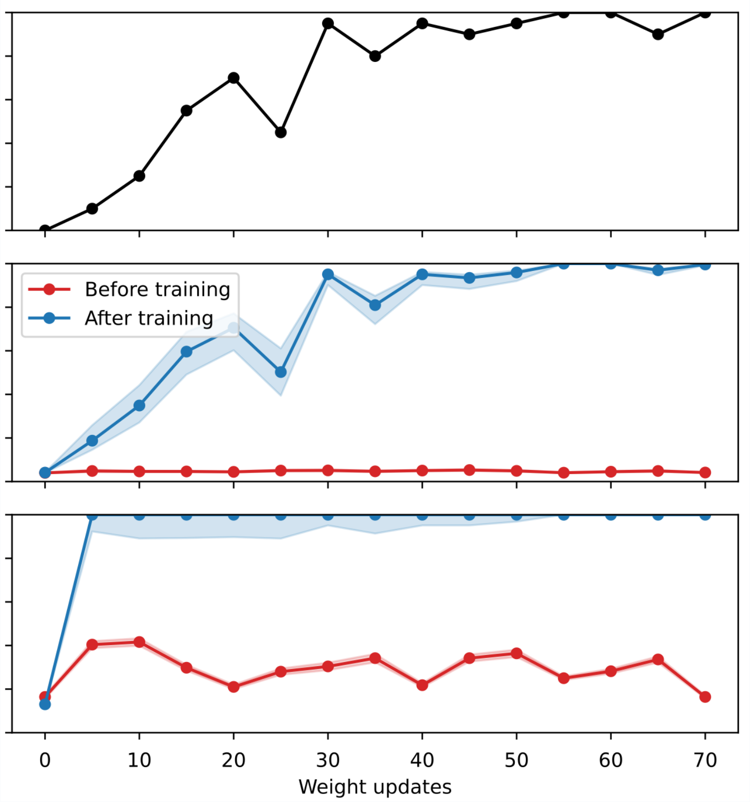
- **Cartpole-v1:** official OpenAI gym env from classic control problems domain
- Continuous state (4D), **discrete action** *(right, left)* problem with **non-linear dynamics**
- Terminate episodes after **max. 500 steps**

- **Big gain in sample-efficiency** and **robustness** for FERL vs DQN

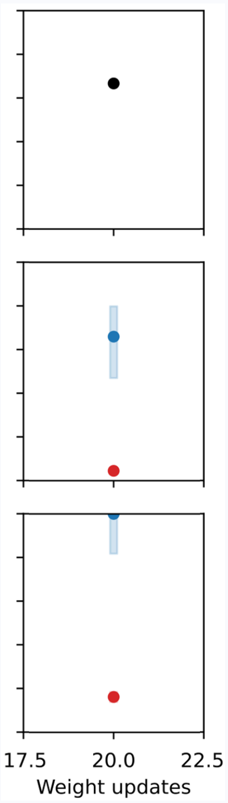
DQN

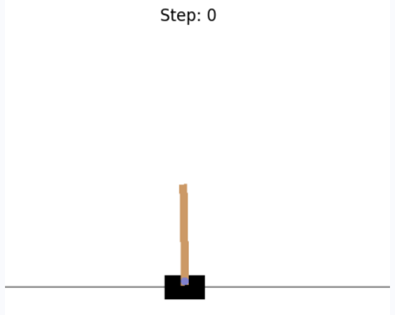


FERL *(simulated QA)*

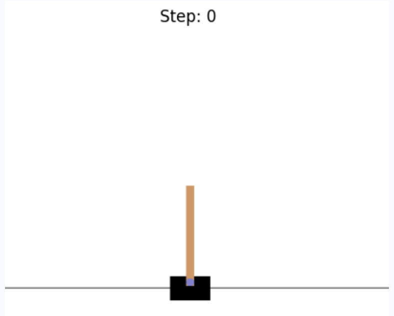


FERL *(trained on D-Wave)*





before



after

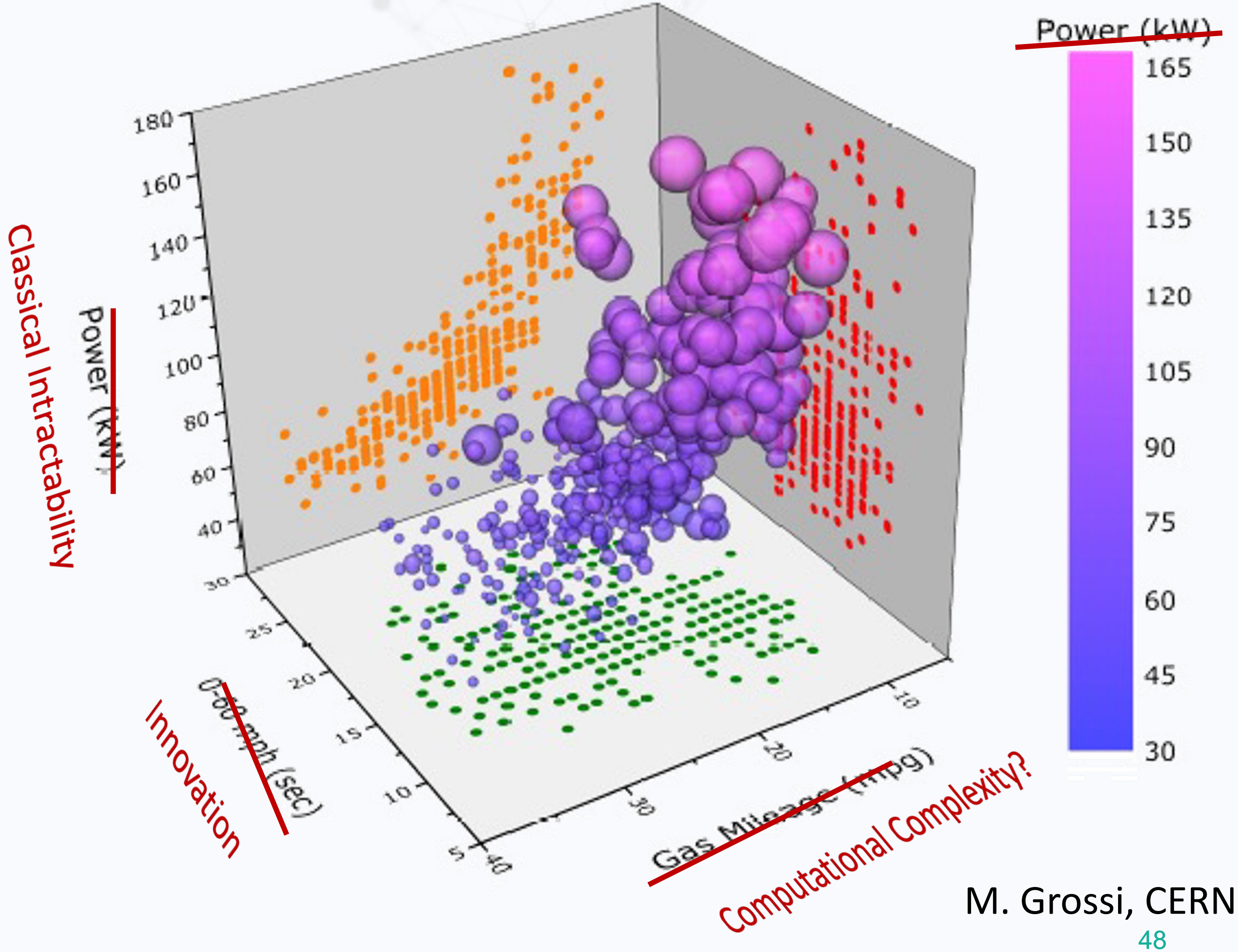
Outlook and open questions

- Quantum technolgies could be revolutionary in terms of computing
- HEP provides challenges to Quantum Computing
  - **What are the most promising applications?**
  - How do we define performance and validate results on **realistic use cases**?

- Experimental data has high dimensionality
  - Can we train Quantum Machine Learning algorithms effectively?
  - Can we reduce the impact of **data reduction** techniques?
- Experimental data is shaped by physics laws
  - Can we leverage them to build better algorithms?

QML Exclusion Region in HEP?

QML is the right solution



Classical Intractability

Innovation

Computational Complexity?

M. Grossi, CERN

Lectures and Hands-On at CERN

- «A practical Introduction to quantum computing», Elias Combarro

https://indico.cern.ch/event/970903/

- «Introduction to quantum computing », Heather Grey

https://indico.cern.ch/event/870515/

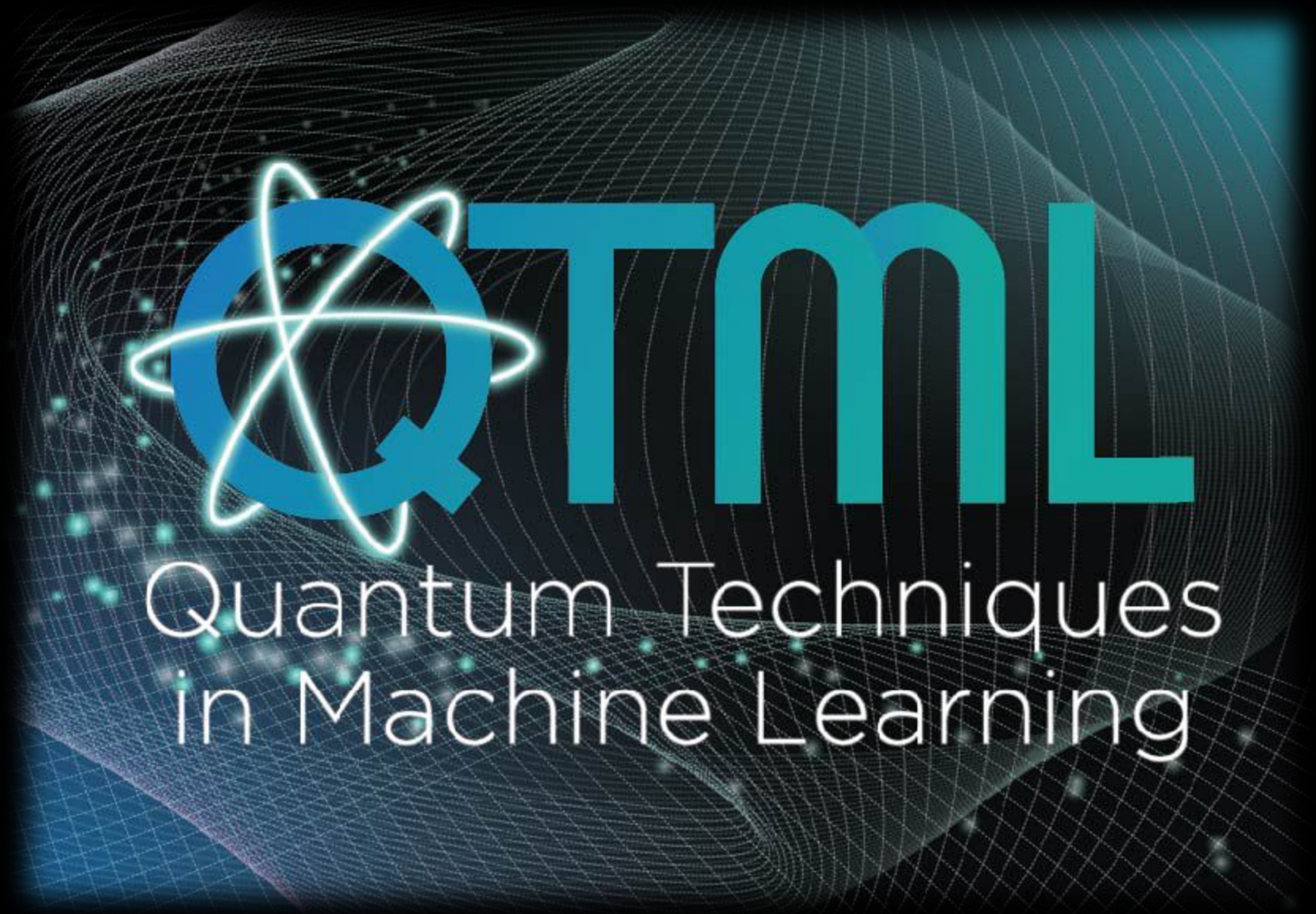
- A set of two hands-on (introduction) sessions for summer students (2023 openlab summer student lectures)

https://indico.cern.ch/event/1293871/

https://indico.cern.ch/event/1293874/

Thank you!

November 20th-24th, 2023
@CERN



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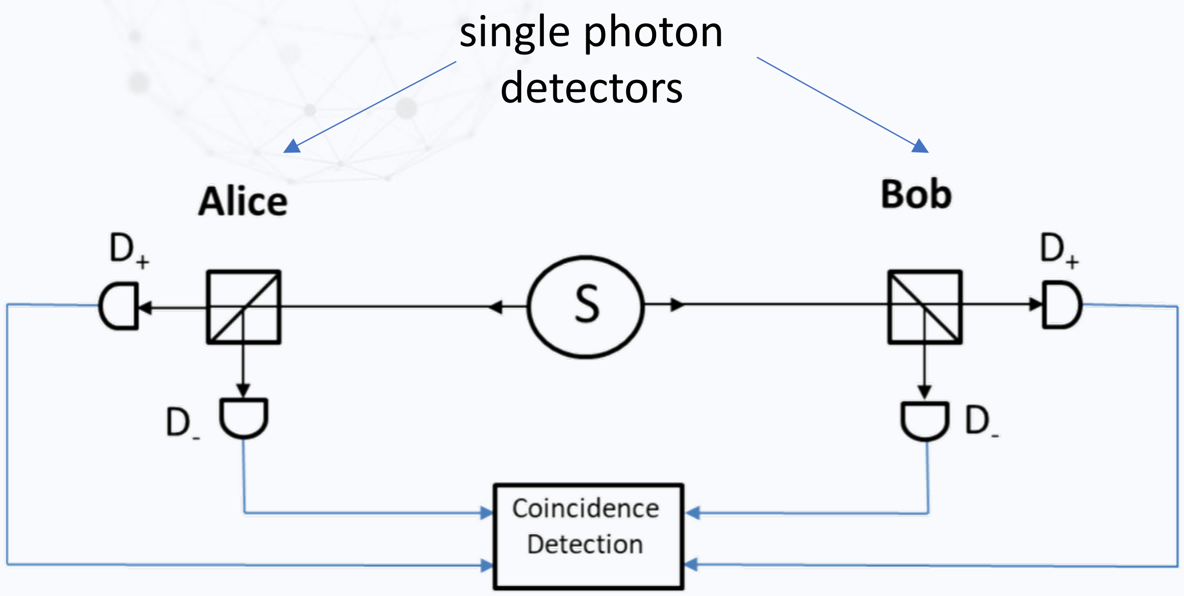
Bell Inequalities

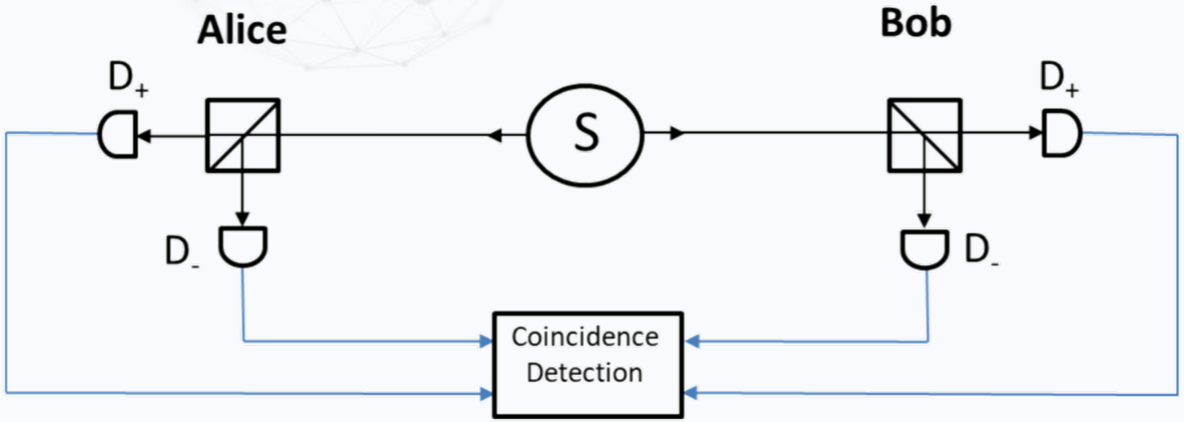
- 1964: Bell inequality are a mathematical proof that no theory based on **local hidden variables** (realism) can reproduce QM results
- 1969: Clauser, Horne, Shimony (CHSH) formulation



- Measure the correlation $E(a, b) = (N_{++} - N_{+-} - N_{-+} + N_{--})/(N_{++} + N_{+-} + N_{-+} + N_{--})$
- Where N_{++}, N_{+-}, N_{-+}, and N_{--} are the number of coincidence events corresponding to the simultaneous detection

NB in a realist theory the measurement outcome is «known» even if the measurement is not performed

Bell Inequalities



For experimental outputs of the form $A_1 = \pm 1$

$$A_1(B_1 + B_2) + A_2(B_1 - B_2) = \pm 2,$$

since $B_1 + B_2 = \pm 2$ and $B_1 - B_2 = 0$ or v.v.

Performing the experiment many times, the correlation is calculated using the ensemble average over the measurements

$$E(a_1, b_1) = \langle A_1 . B_1 \rangle$$

$$S = |E(a_1, b_1) + E(a_1, b_2) + E(a_2, b_1) - E(a_2, b_2)|$$

Classical theory: $S < 2$

Quantum mechanics: $S = 2\sqrt{2}$

since $E(a_1, b_1) = -\boldsymbol{a}_1 . \boldsymbol{b}_1$ for $|\psi_-\rangle$

and experiment directions can be chosen so that:

$$\boldsymbol{a}_1 . \boldsymbol{b}_1 = \boldsymbol{a}_1 . \boldsymbol{b}_2 = \boldsymbol{a}_2 . \boldsymbol{b}_1 = -\boldsymbol{a}_2 . \boldsymbol{b}_2 = 1/\sqrt{2}$$