Quantum Computing and HEP

(seen by an HEP experimental physicist)

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Thanks to

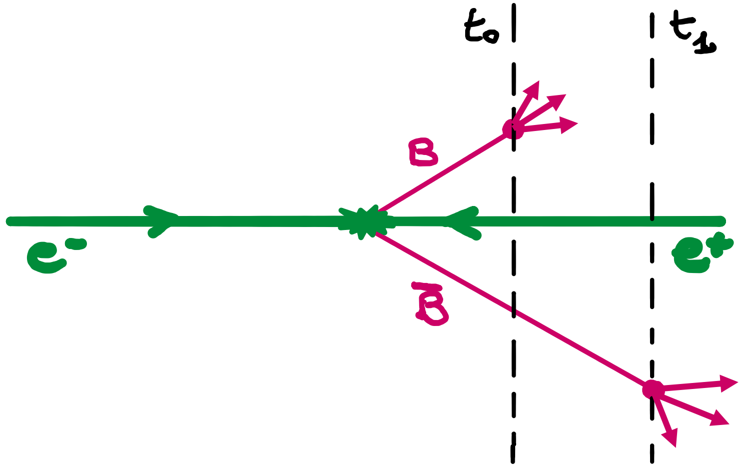
K. Boras, M.L. Martínez, S. Monaco, D. Nicotra, V. Radescu, L. Sestini, S. Vallecorsa, D. Zuliani

First quantum revolution: discovery quantum

- Discover and understand quantum phenomena
- Nobel prizes: Max Karl Ernst Ludwig Planck,1918 and Niels Bohr, 1922

Quantum properties used in several applications: solar cells, laser, etc.

In HEP, used in B-factories: $\Upsilon(4S) \rightarrow B\bar{B}$ in a coherent antisymmetric quantum state evolving coherently until



one **B** decays, $\mathbf{t_0}$ only at this time, $\mathbf{t_0}$, the nature of the other **B** is defined

Second quantum revolution: quantum technology

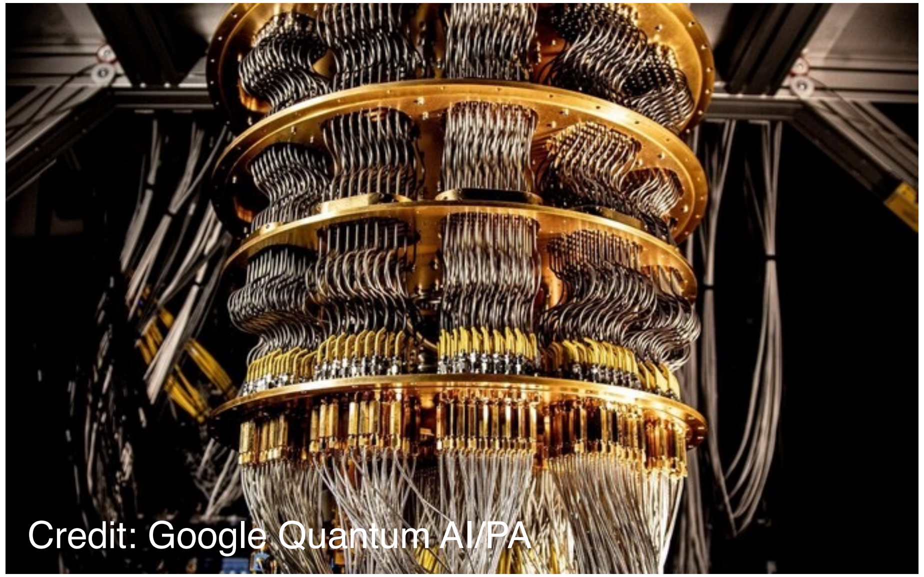
Nobel prize: Alain Aspect, John F. Clauser and Anton Zeilinger, 2022

Engineer quantum phenomena to our own ends, quantum engineering:

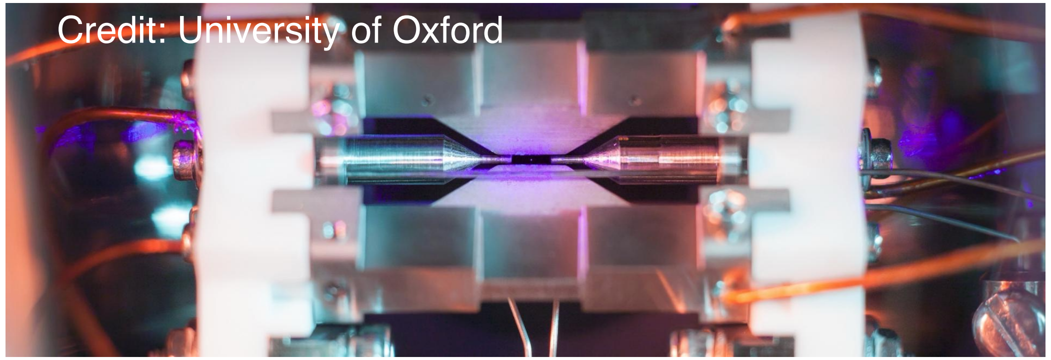
- Quantum science allows to understand the elements periodic table quantum engineering allows to create a new element with new optical and electrical properties.
- In our case: quantum computers!

See talk of Makoto Fujiwara for quantum applications

Major Quantum computers

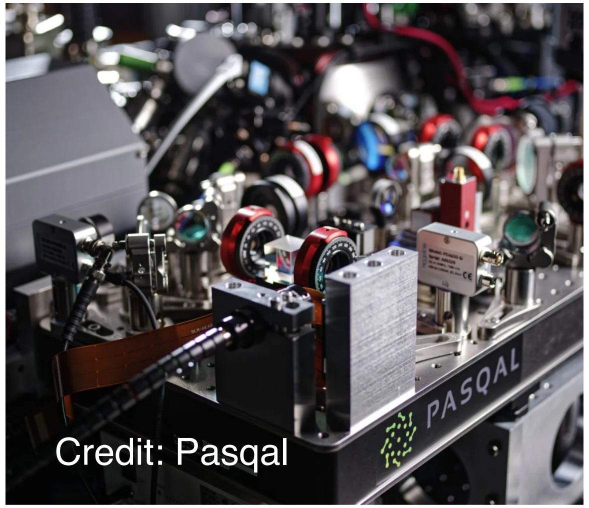


Superconductors
Superconducting electronic junctions below 15mK behave as quantum systems with discrete energy levels
Ex. Google, IBM, Rigetti

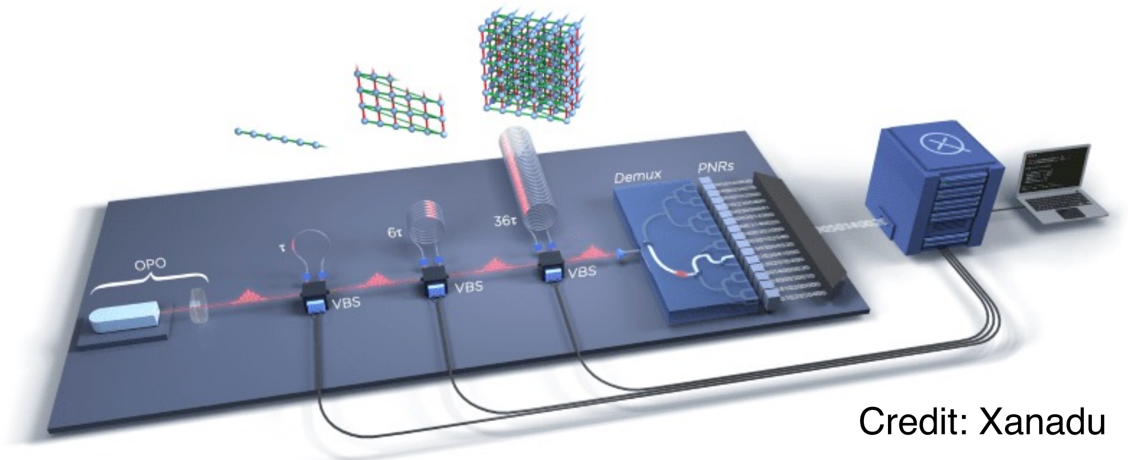


Trapped ions
Ions can be confined in a free space by using electromagnetic traps and manipulated with lasers
Ex. IonQ, Quantinuum

Neutral atoms
Ordered neutral atoms in 2D and 3D arrays manipulated with lasers
Ex. Pasqal



Major Quantum computers cont'd

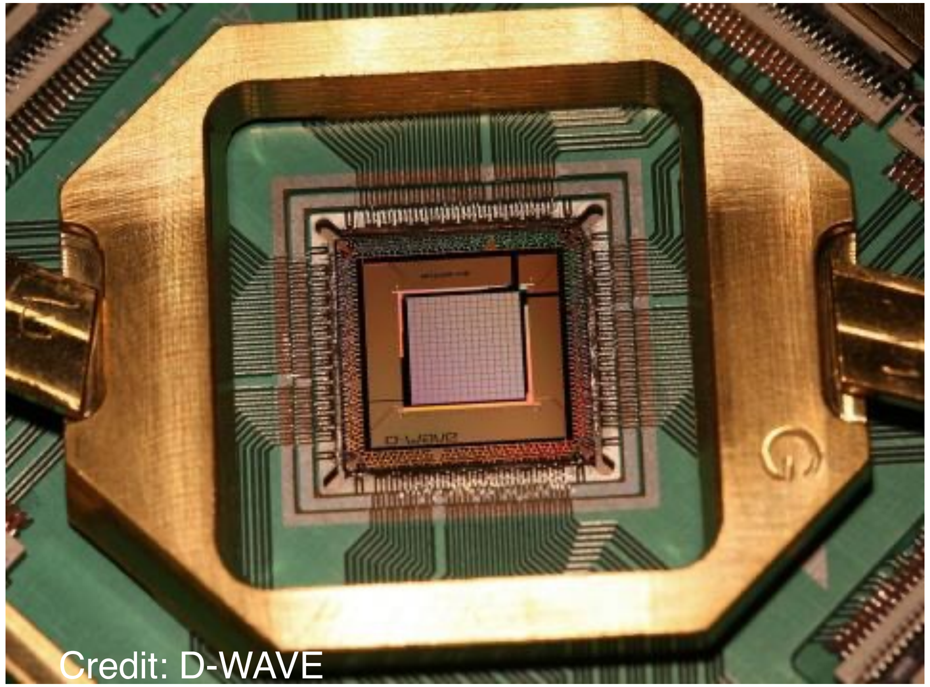


Credit: Xanadu

Optics

Linear optics elements use photons as information carriers and photon detectors to detect quantum information

Ex. Xanadu


Credit: D-WAVE

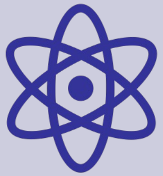
Annealing

Quantum processing unit, QPU, built by qubits lattice with different topologies.

Hardware relies on metal loops of niobium with tiny electrical currents running through them.

Ex. D-Wave

Each computer technology has its own software to use it: gates based or customizable Hamiltonian



Could quantum computing offer a new path for HEP scientific computing?

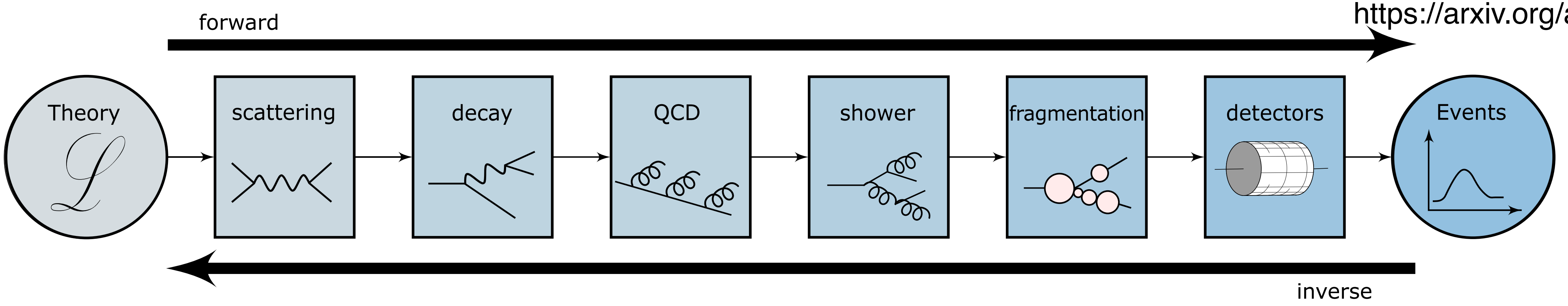
Advantages:
- possible quantum speed-up in processing time
- sensitive to quantum correlations
- increased expressivity*

Do we, HEP community, need to change “computing” paradigm? How to proceed?

*ability to generate states representative of the Hilbert space.

Experimental high energy physic data

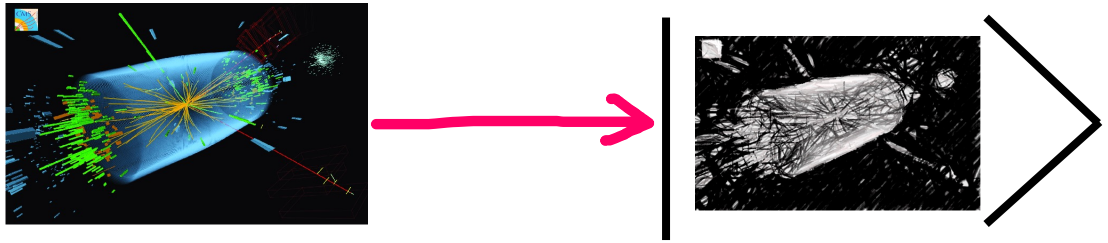
A. Butter et al.
Snowmass contribution
https://arxiv.org/abs/2203.07460



HEP experiments use computers in the two directions of the arrows:

- predict results from an experiment, for example detector simulation
- data analysis for models interpretation or search for anomalies

In both cases, HEP experiments are based on *measurements* → HEP data are not quantum data need to be transformed to be processed in quantum computers: quantum embedding



What goes in the quantum state depends on the goal: track segment, event observables, …

How to use a quantum computer

System preparation: data embedding, vectors and operators initialization → Computation: operators, that implement algorithms, applied to vectors: → Measurement: evaluation of probability distribution of final state

HEP use cases usually require large number of qubits, $\mathcal{O}(10^3)$, ⇒ simple or simplified applications used

Quantum computers have:

- not-so-large number of qubits: $30 \div 100$ now, $100 \div 300$ near future, ~ 1000 in few years
- quantum error* correction not yet at the level to guarantee fault tolerant computing

⇓

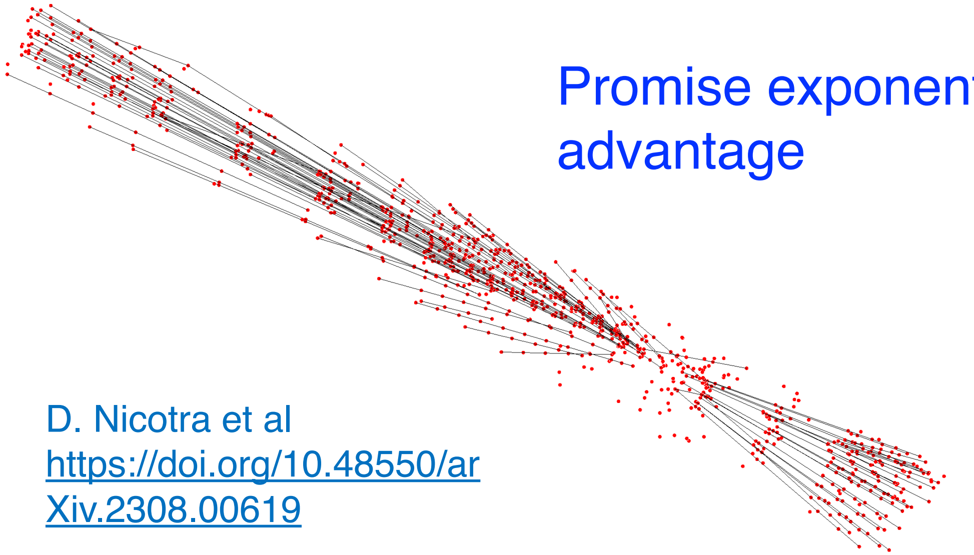
quantum simulators: classical algorithms to be executed on classical computers emulating quantum computer
If the number of qubits is large quantum computer can not be simulated.

* Quantum errors: quantum noise and states decoherence

Example 1: Tracks reconstruction

Track identification is a challenge for high granularity tracking systems, it scale as $N_{hits}^{2\div3}$
Quantum methods could provide speed-up

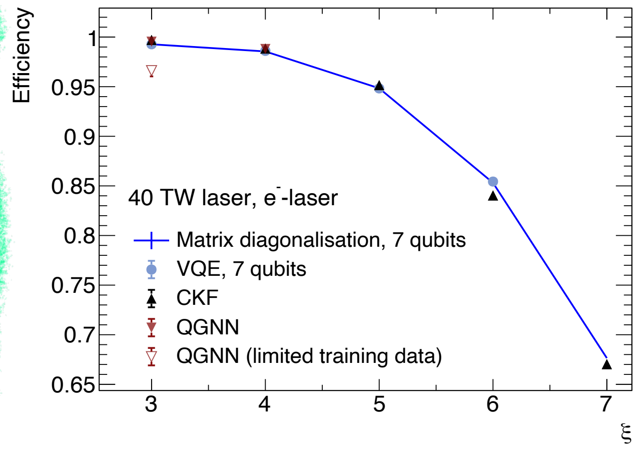
- Simulated $B_s \rightarrow \varphi\varphi$ in LCHb: tracks in vertex detector reconstructed with quantum algorithm (Harrow-Hassidim-Lloyd)
- Global approach
- Quantum implementation with toy, because high depth circuit required

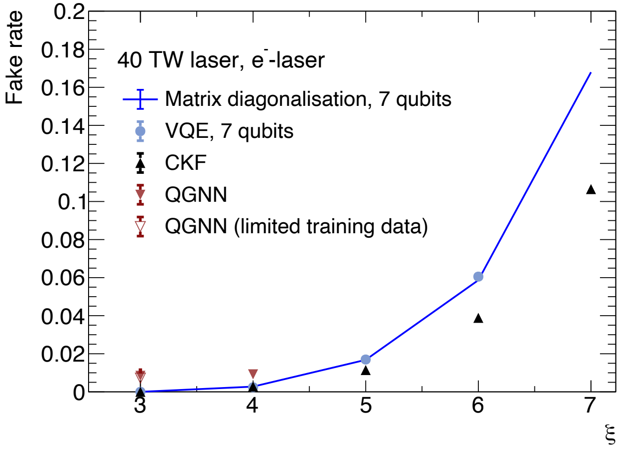


Promise exponential advantage

D. Nicotra et al
https://doi.org/10.48550/arXiv.2308.00619

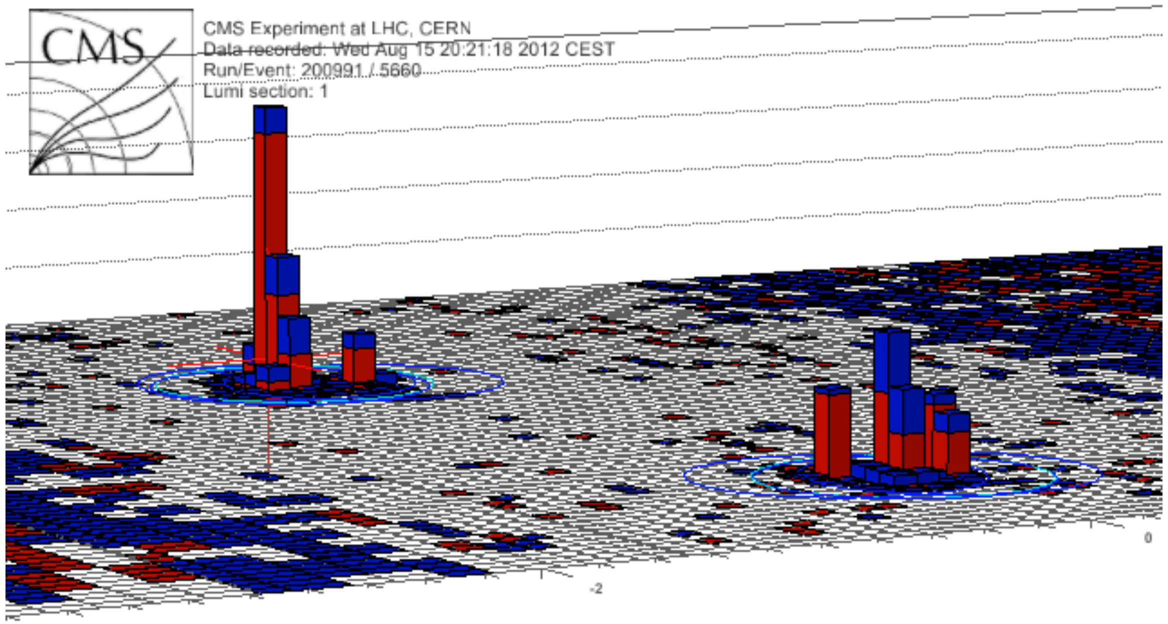
- Positrons in LUXE experiment @DESY to study QED in strong-field regime, ξ: laser intensity
- Tracking: 4 layers of detector
- Positron rate spans $10^{-4}\div10^{6}$
- Pre-select doublets/triplets
- Quantum methods compared to Combinatorial Kalman Fitter





A. Crippa et al, https://arxiv.org/abs/2304.01690

Example 2: Jet reconstruction



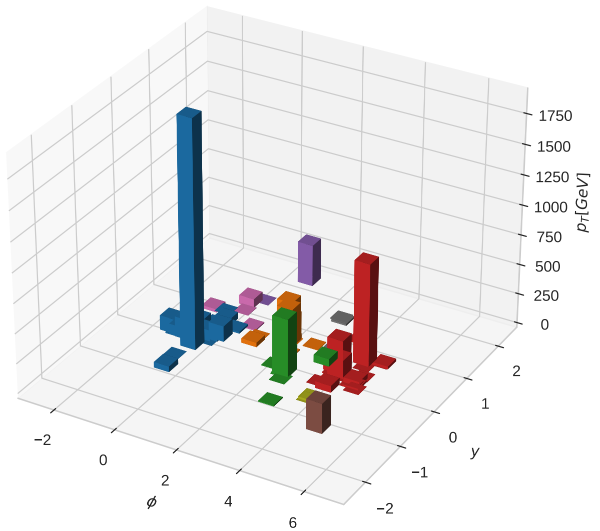
Use generalized k_T-algorithm

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p})\Delta R_{ij}^2/R^2$$

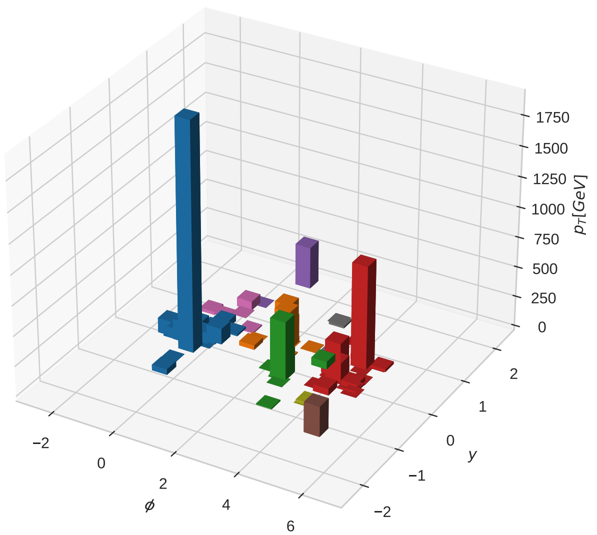
p =-1 -> anti-k_T
p =-0 -> Achen/Cambridge
p =1 -> k_T

Data set: 300 three-dimensional vectors (massless partons) recoiling against small number of tagged particles.

- $\Delta R_{i,j}^2$: computed classically
- Minimum of the distance computed with quantum algorithm
- Due to the limitation of the noise on quantum computer results are obtained in an error-free quantum simulator.



anti-k_T R=1

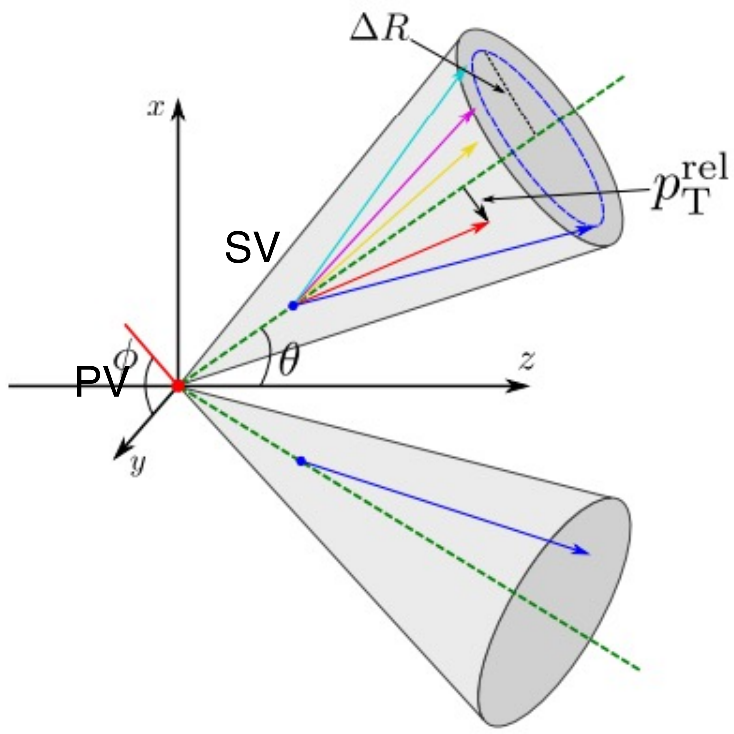


quantum anti-k_T R=1, $\varepsilon_c = 0.99$

J. J. Martinez de Leijarza et al. PhysRevD.106.036021

Example 3: Jet identification

Jet tagging: identification of the flavor of the quark (b, c, light) that generate the jet



[A. Gianelle et al., J. High Energ. Phys. 2022, 14 (2022)]

Algorithms based on machine learning (ML) developed and tuned in the years: high efficiency and high purity is reached. See talk of Lukas Heinrich

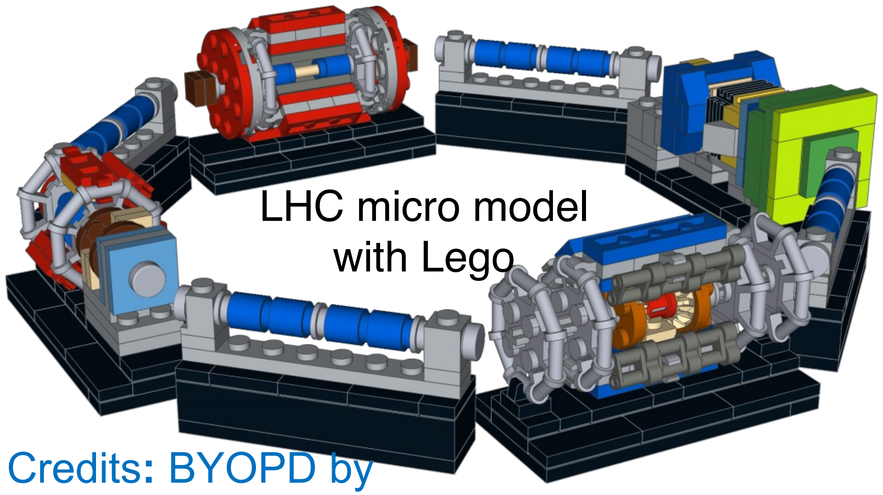
Quantum machine learning algorithm developed @LHCb

- ❃ Use reduced number of features to keep low number of qubit
- ❃ Run on noiseless simulator and tested on real hardware
- ❃ Quantum noise evaluated not impacting with a low number of qubits
- ❃ Performance similar to ML

Findings:

- ✓ Amount of data needed for training is much less in QML
- ✓ Results depends on the implementation of the algorithm on quantum computer ⇒ co-design mandatory
- ✓ Quantum correlations among features could give insight on jet structure

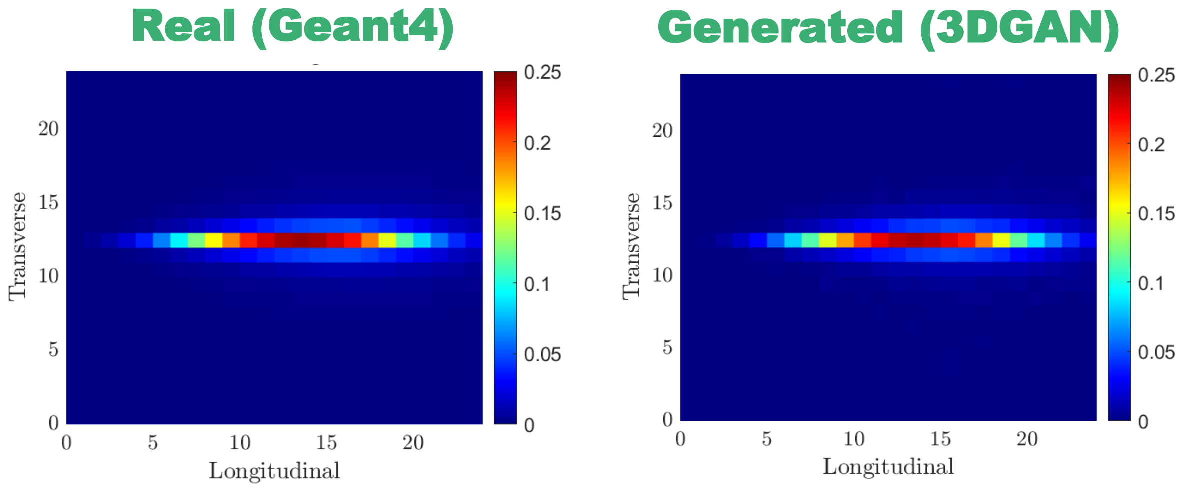
Example 4: Detector simulation



Credits: BYOPD by
Sascha Mehlhase

Detector simulation at LHC, HL-LHC experiments use about 50% of CPU
Future accelerator detectors will need more due to increased granularity and precision required.
See Borut Kersevan, Graeme Stewart talks

Generative Adversarial Network (GAN) models are successful



Use of quantum GAN (qGAN)

- Models applied with success on quantum finance

qGAN in HEP

- Difficult to reproduce energy probability distribution over pixel, lot of information -> dedicated approach (dual-parametrized quantum circuit)
- Simulate calorimeter longitudinal energy distribution only along calorimetry depth for 4 pixels to reduce number of qubits
- Encouraging results, room for improvement

S. Chang, EPJ Web Conf. Volume 251 (CHEP 2021)

- Test different circuit approach to simulated calorimeter test beam prototypes

Moving toward an organized effort

- Working group in Snowmass CompF6: Quantum computing and session in Seattle
- Snowmass Computational Frontier: Topical Group Report on Quantum Computing https://doi.org/10.48550/arXiv.2209.06786
- Initiative promoted by CERN, DESY and IBM: working group on Quantum Computing for HEP formed Nov. 2022, QC4HEP, participation from several HEP Institutes (EU, US, Japan + other countries)

Joint effort across HEP community, experiment and theory

Paper published on arxiv https://doi.org/10.48550/arXiv.2307.03236

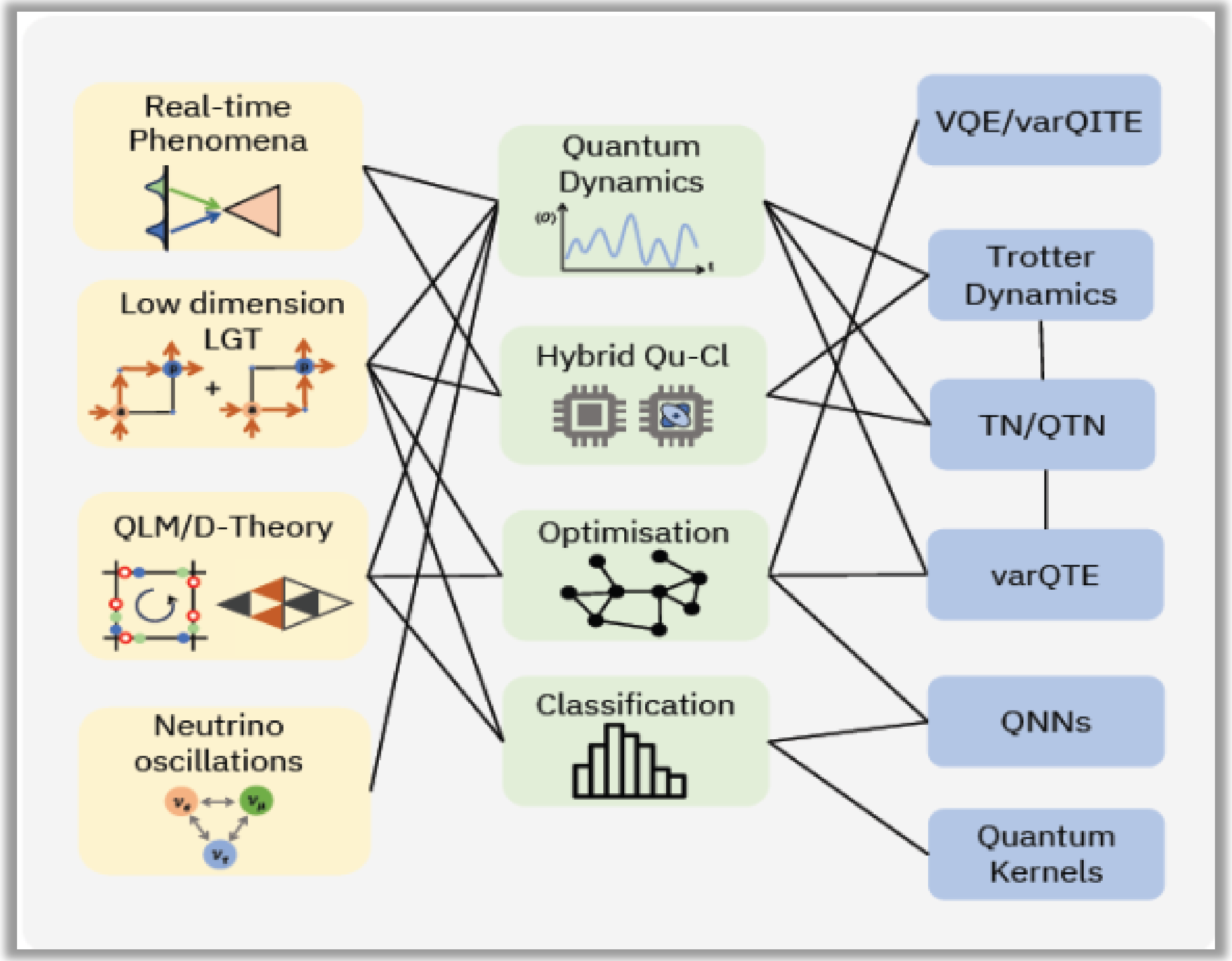
Quantum Computing for High-Energy Physics: State of the Art and Challenges. Summary of the QC4HEP Working Group

Alberto Di Meglio, Karl Jansen, Ivano Tavernelli, Constantia Alexandrou, Srinivasan Arunachalam, Christian W. Bauer, Kerstin Borras, Stefano Carrazza, Arianna Crippa, Vincent Croft, Roland de Putter, Andrea Delgado, Vedran Dunjko, Daniel J. Egger, Elias Fernandez-Combarro, Elina Fuchs, Lena Funcke, Daniel Gonzalez-Cuadra, Michele Grossi, Jad C. Halimeh, Zoe Holmes, Stefan Kuhn, Denis Lacroix, Randy Lewis, Donatella Lucchesi, Miriam Lucio Martinez, Federico Meloni, Antonio Mezzacapo, Simone Montangero, Lento Nagano, Voica Radescu, Enrique Rico Ortega, Alessandro Roggero, Julian Schuhmacher, Joao Seixas, Pietro Silvi, Panagiotis Spentzouris, Francesco Tacchino, Kristan Temme, Koji Terashi, Jordi Tura, Cenk Tuysuz, Sofia Vallecorsa, Uwe-Jens Wiese, Shinjae Yoo, Jinglei Zhang

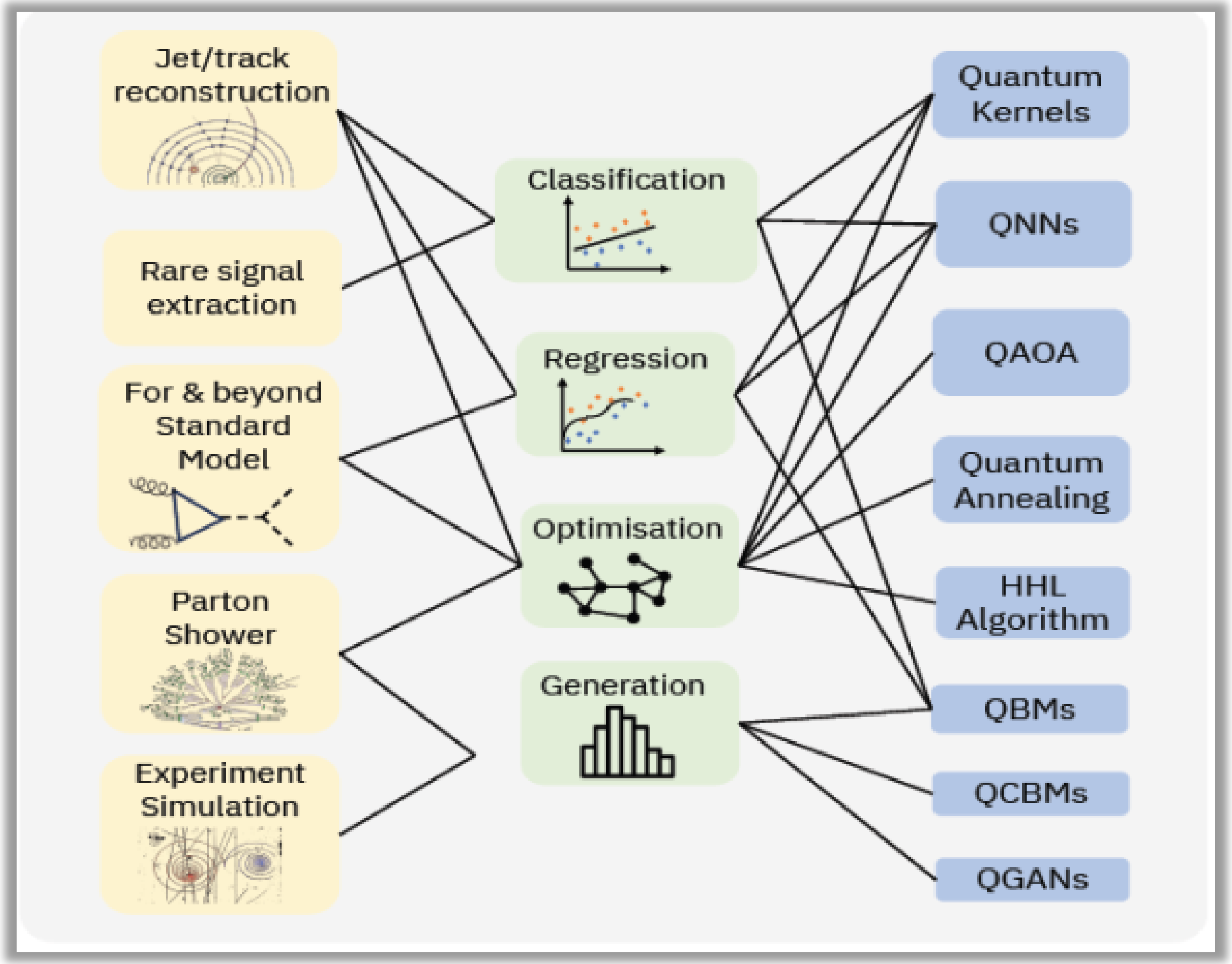
Quantum computers offer an intriguing path for a paradigmatic change of computing in the natural sciences and beyond, with the potential for achieving a so-called quantum advantage, namely a significant (in some cases exponential) speed-up of numerical simulations. The rapid development of hardware devices with various realizations of qubits enables the execution of small scale but representative applications on quantum computers. In particular, the high-energy physics community plays a pivotal role in accessing the power of quantum computing, since the field is a driving source for challenging computational problems. This concerns, on the theoretical side, the exploration of models which are very hard or even impossible to address with classical techniques and, on the experimental side, the enormous data challenge of newly emerging experiments, such as the upgrade of the Large Hadron Collider. In this roadmap paper, led by CERN, DESY and IBM, we provide the status of high-energy physics quantum computations and give examples for theoretical and experimental target benchmark applications, which can be addressed in the near future. Having the IBM 100 x 100 challenge in mind, where possible, we also provide resource estimates for the examples given using error mitigated quantum computing.

Sub-groups of QC4HEP and activities

Theory



Experiments



https://doi.org/10.48550/arXiv.2307.03236

Within the CERN QTI phase 2:

- Collaborate in each sub-WG and across them to make progress
- Establish synergies and collaboration across WGs
- Participate to the IBM 100x100 challenge:

Some use cases will be selected to develop the methods and algorithms on the IBM devices to assess:
- actual capabilities of the devices,
- scalability, performance and results of the approaches

CERN is a Hub Member of the IBM Q-Network
Access to IBM hardware based on quotas for Hub members

Outlook

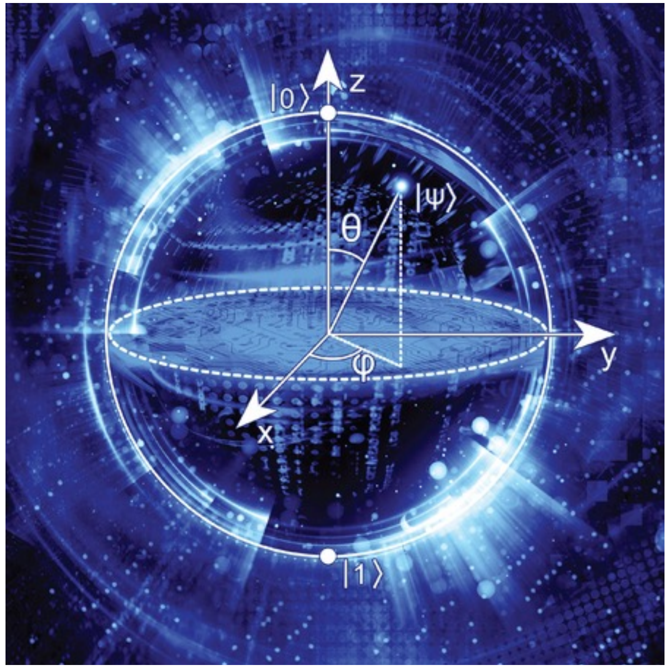
Quantum Computers are available exploiting different technologies, companies and large labs cooperate to provide hardware with more qubits, more depth, more stable and less noise.

HEP community is just starting to play with this new toy, limitations due:

- low number of qubits and small depth
- noise
- data embedding

Nevertheless, results are encouraging and somehow intriguing:

- speed-up is promised
- new insight on physics processes may be possible by study quantum correlations



New computing paradigm is needed in HEP to exploit the new hardware

BACKUP SLIDES

Example : Anomaly detection

K. A. Woźniak et al. https://arxiv.org/abs/2301.10780

BSM process treated as anomalies:

- Randall-Sundrum gravitons decaying to two W-bosons (wide and narrow).
- Scalar boson A decaying to a HZ bosons ($A \to HZ$), $H \to ZZ$, resulting in a ZZZ final state.
- Resonances 1500-4500 GeV in steps 1000 GeV

Data: pp →jets using QCD

New method, convolutional autoencoder (AE) developed to reduce the dimension of the problem
QML methods developed to detect anomalies: kernel machines and clustering algorithms.

Results

Kernel Machine Run	AUC	$\langle \mathrm{tr}\rho^2 \rangle$
Hardware $L = 1$	0.844	0.271(6)
Ideal $L = 1$	0.999	1
Hardware $L = 3$	0.997	0.15(2)
Ideal $L = 3$	1.0	1
Classical	0.998	-

L: repetition of the encoding
AUC: Area under the curve
⟨trρ2⟩: mean purity of the states

Example : Event generation

Event generation, even if great interest for experimental physicists, is an effort driven by theorist physicist:

- Conditional Born machine for Monte Carlo event generation, O. Kiss et al., Physical Review A 106, 022612 (2022)
- Style-based quantum generative adversarial networks for Monte Carlo events, C. Bravo-Prieto et al., Quantum 6, 777 (2022)