CERN

The CERN Quantum Technology Initiative

Results from first pilot projects

QUANTUM
TECHNOLOGY
INITIATIVE

Sofia Vallecorsa

AI and Quantum Research - CERN openlab

CERN

CERN Quantum Technology Initiative

Strategy and Governance

Joint HEP R&D Programme

CERN Management

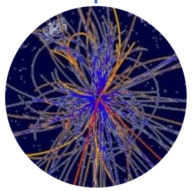
Advisory Board (**representation of the Member States**)

Coordination

QT Initiative Management

R&D

Sensing, Detectors R&D



Computing & Engineering

Communication & Networks

Quantum Simulation & Theory

Collaborations

Academic Programmes / Industrial Collaborations

CERN Quantum Tecnology Initiative

Strategy and long-term benefits

R&D under a common vision and a shared roadmap

Assess the impact of quantum technologies on High Energy Physics research

Build the required knowledge and capacity to create impact

Implementation and execution

Concrete R&D objectives

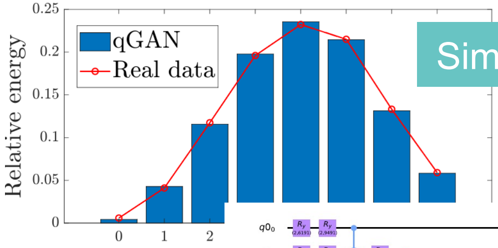
International education and training programs with leading experts, universities and industry

Knowledge sharing within High Energy Physics and beyond

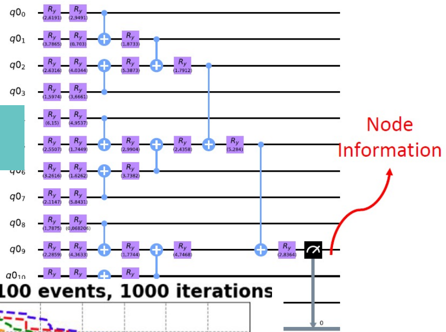
QUANTUM TECHNOLOGY INITIATIVE

R&D projects and Activities

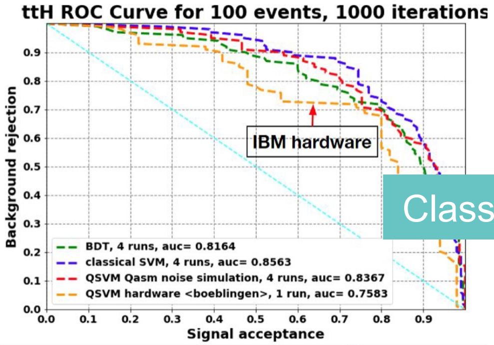
Computing



Simulation

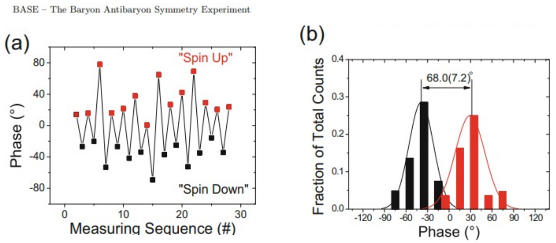


Reconstruction



Classification

Sensing

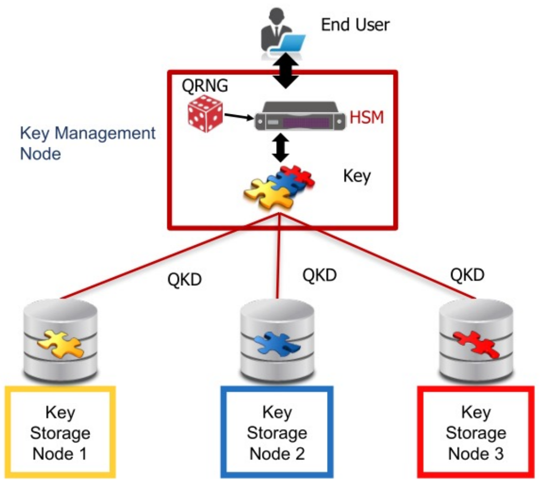


https://doi.org/10.1140/epjst/e2015-02607-4

Low energy measurements, quantum states measurements, nano-technologies

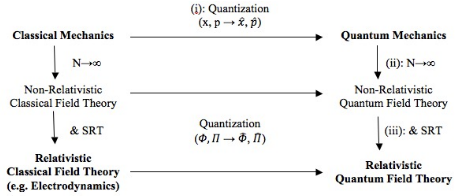
Future HEP detectors

Communications

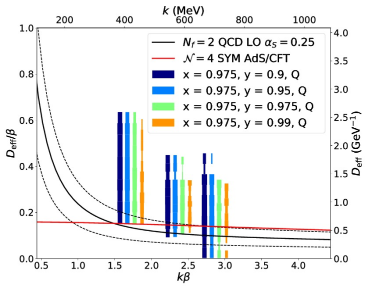


openQKD Infrastructures Quantum Internet

Theory



Quantum Field Theory



https://cds.cern.ch/record/2703396

Lattice QCD

Many pilot projects started as part of the **CERN openlab quantum** programme (https://openlab.cern/quantum)

QC@CERN

- **Development and optimization of algorithms** targeted for **realistic** use cases
- Build expertise on **state-of-the-art software stack**
    - Provide **resource access** to the community for R&D
- **Joint projects** with industry and other sciences

QC Algorithms

- Quantum Machine Learning algorithms are a primary candidate for investigation
  - Increasing use of such techniques in many computing and data analysis flows
  - Can be built as **hybrid models** where quantum computers act as accelerators where classic computing is not computationally efficient
- Classification, pattern recognition, anomaly detection
- Clustering, optimisation
- Efficient data handling is a challenge
  - Data encoding or reduction is required for practical use of NISQ devices

Example pilot projects

Quantum Generative Adversarial Networks for detector simulation

arXiv:2103.15470, arXiv:2101.11132

Quantum Tree Tensor Networks for particle trajectory reconstruction

arXiv:2007.06868, arXiv:2012.01379, arXiv:2109.12636

Quantum Classifiers for Higgs boson identification

arXiv:2104.07692

Hybrid quantum-classical tracking hits embedding

EPJ Web of Conferences (Vol. 251, p. 03065)

Quantum algorithms for anomaly detection

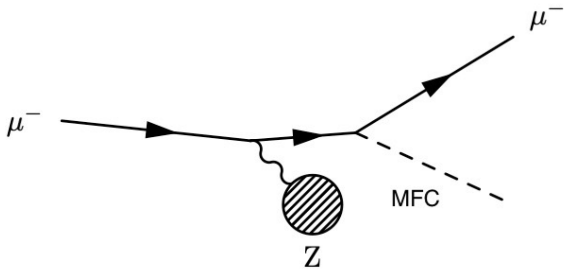
Quantum Boltzman Machines for beams optimization in accelerators

Quantum Born Machines for event generation

Quantum Born Machine for event generation

Muon Force Carriers predicted by several theoretical models:

- Could be detected by muon fixed-target experiments (FASER) or muon interactions in calorimeters (ATLAS).

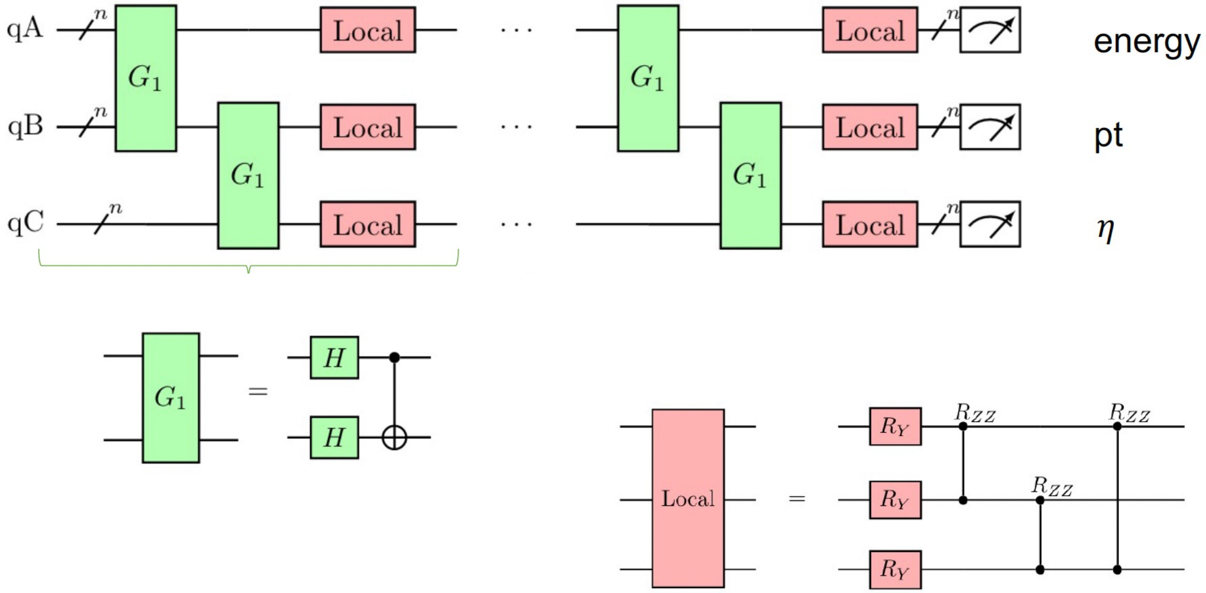


Generate **E, p_t, η** of outgoing muon and MFC

Sample from variational wavefunction $|\psi(\theta)\rangle$ with $p_\theta(x) = |\langle x|\psi(\theta)\rangle|^2$ given by the Born rule

Generate **discrete PDFs** (continuous in the limit #qubits → ∞)

Maximum Mean Discrepancy loss function and gaussian kernel with $\sigma \in [0.1,1,10,100]$



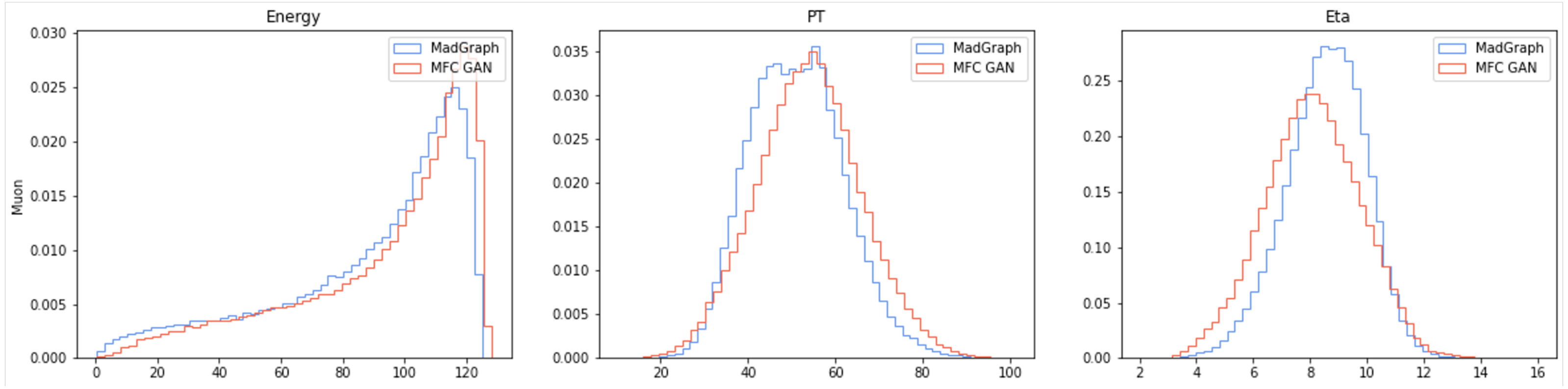
$$MMD(P,Q) = \mathbb{E}_{\substack{X\sim P\\Y\sim P}}[K(X,Y)] + \mathbb{E}_{\substack{X\sim Q\\Y\sim Q}}[K(X,Y)] - 2\mathbb{E}_{\substack{X\sim P\\Y\sim Q}}[K(X,Y)]$$

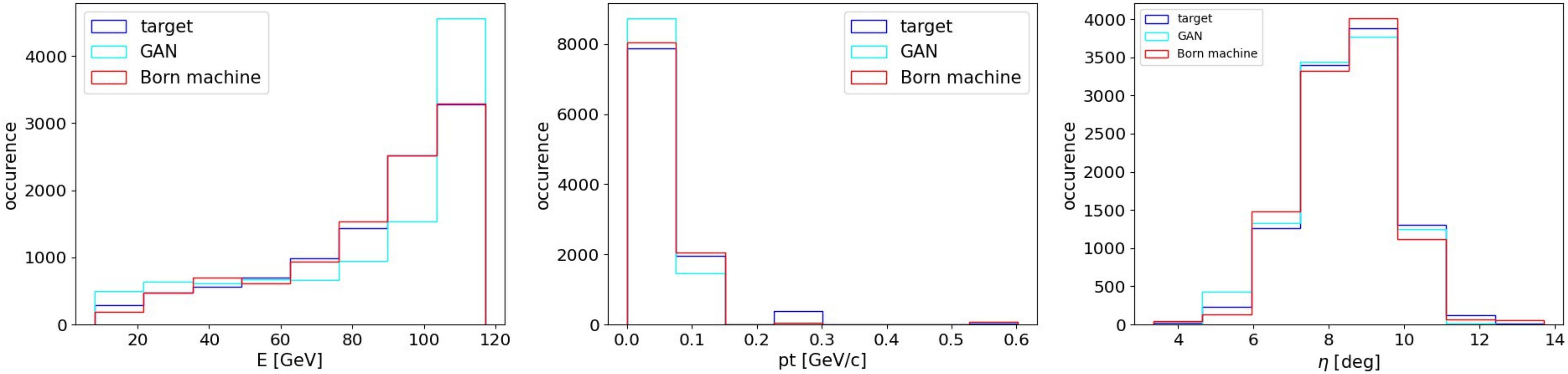
Galon, I, Kajamovitz, E et al. "Searching for muonic forces with the ATLAS detector". In: Phys. Rev. D 101, 011701 (2020)
Coyle, B., Mills, D. et al, "The Born supremacy". In: npj Quantum Inf 6, 60 (2020)

Results

Generate multiple features

Comparison to classical GAN and MadGraph

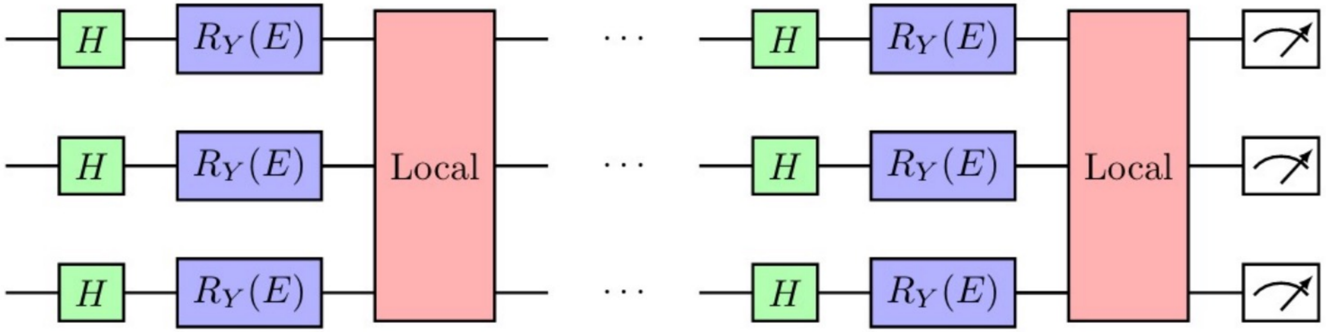




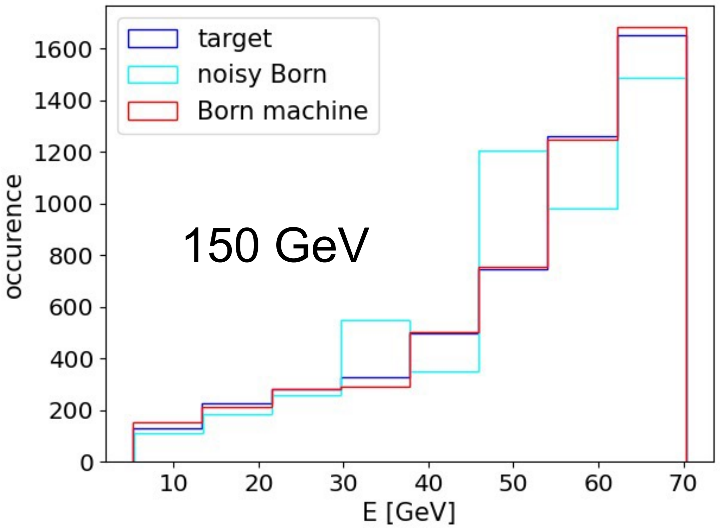
Conditional Born Machine

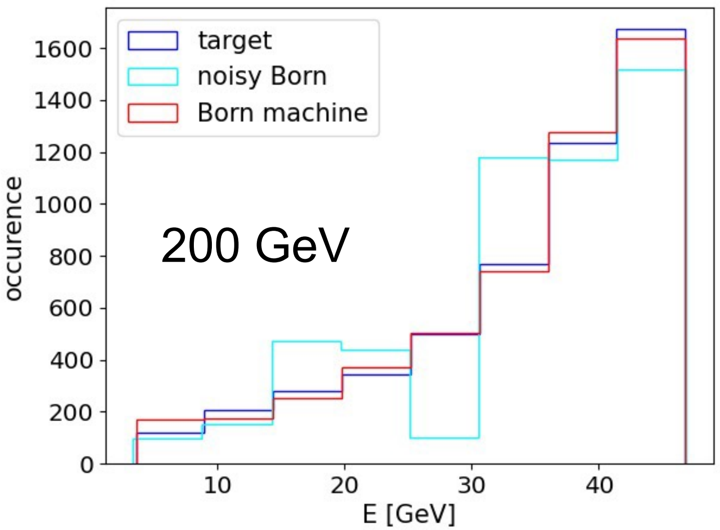
Encode $E_{\mu,i}$ condition using parametrized rotations

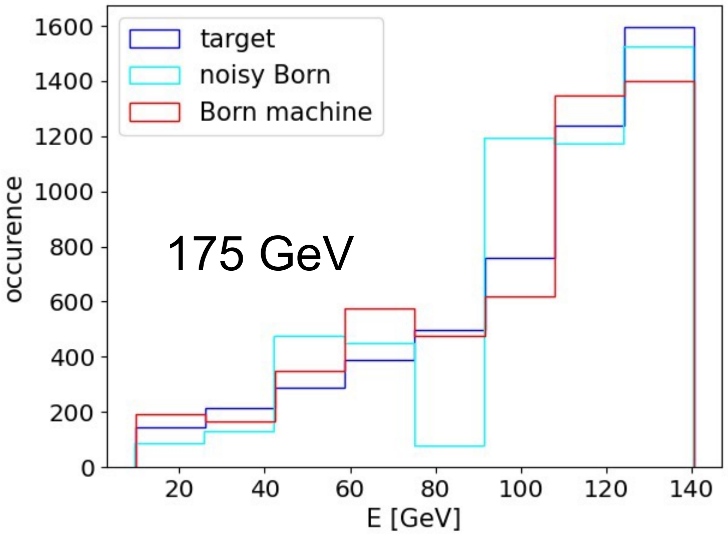
Interpolation: train on 150 and 200 GeV muons and predict 175 GeV signal



Data re-uploading makes the quantum circuit more expressive as function of the data
Noise model according to IBM Q Casablanca







Hardware and Software Resources

- Focus on **tools for software development** and testing
- Access to **different resources:** classical (simulators) and quantum hardware
  - Cluster with different quantum computing simulators for development up to 20-25 qubits
  - ATOS QLM appliance for simulations up to 34 qubits
  - Access to the IBM Q systems
- Evaluate **different hardware solutions**: digital (semiconductors, ions, photons) and annealer

- Building shared experience on different **computing simulators**, real **NISQ hardware**, and hybrid infrastructures where **cloud computing**, **HPC resources** and **quantum computers** interact is key to capacity building for the future

Chang S.Y. *et al.*, Running the Dual-PQC GAN on Noisy Simulators and Real Quantum Hardware, QTML2021, ACAT21

Benchmarks on hardware

Train models using noisy simulator and test the inference of the model on the superconducting (**IBMQ**) and trapped-ion (**IONQ**) quantum hardware

- For IBMQ machines, choose the qubits with the lowest CNOT gate error

Device	Readout error CX error	$D_{KL}/D_{KL,ind}$ $(\times 10^{-2})$
ibmq_jakarta	0.028 $1.367 \cdot 10^{-2}$	0.14 ± 0.14 6.49 ± 0.54
ibm_lagos	0.01 $5.582 \cdot 10^{-3}$	0.26 ± 0.11 6.92 ± 0.71
ibmq_casablanca	0.026 $4.58 \cdot 10^{-2}$	4.03 ± 1.08 6.58 ± 0.81
IONQ	NULL $1.59 \cdot 10^{-2}$	1.24 ± 0.74 10.1 ± 5.6

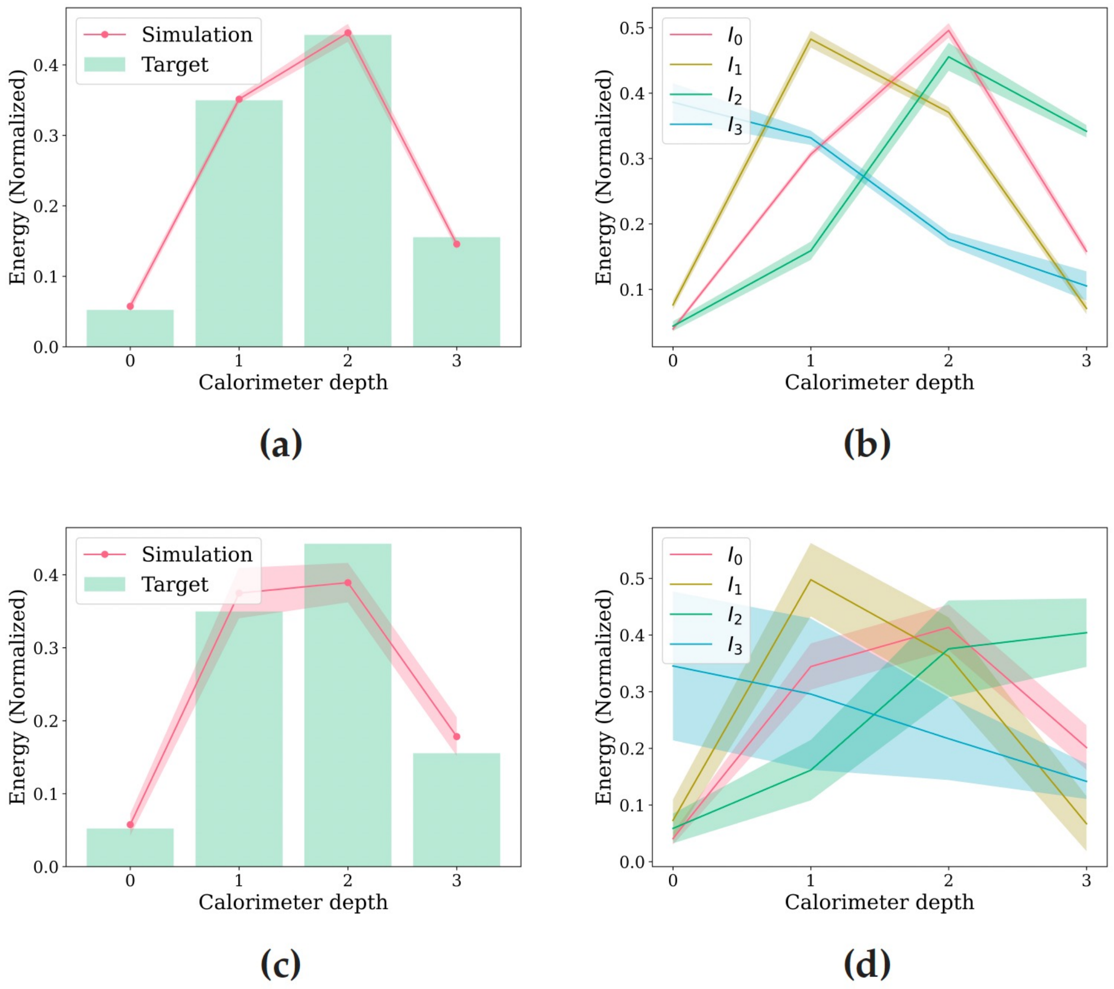
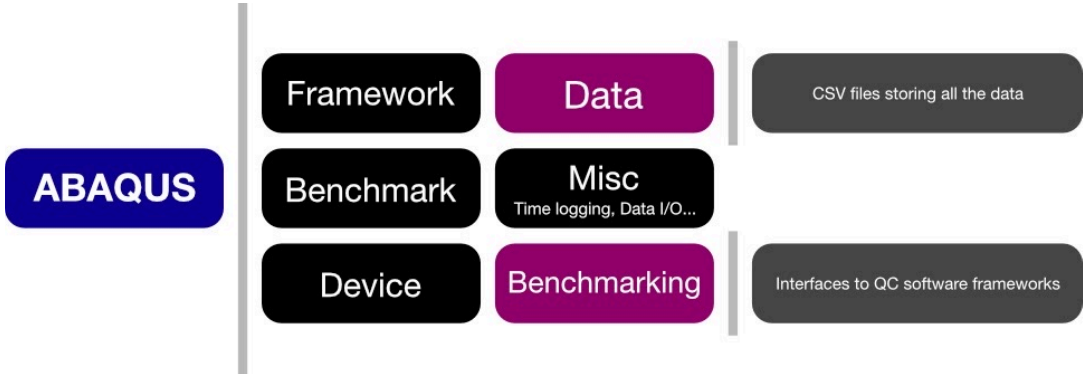


Figure 4: Mean (a,c) and individual images (b,d) obtained by inference test on ibmq_jakarta (a,b) and IONQ (c,d).

ABAQUS - Automated Benchmarking of Algorithms for QUantum Systems

A benchmarking platform to provide consistent and reliable benchmarks for both software frameworks and hardware devices.

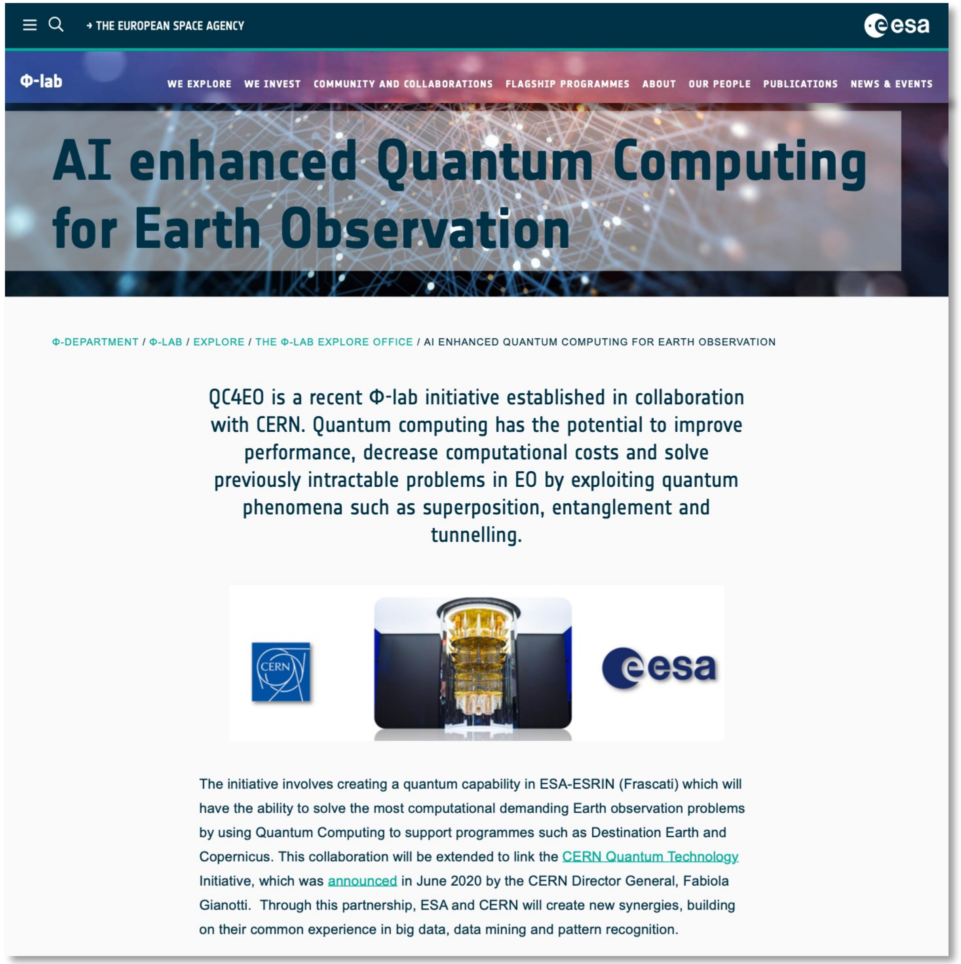
- **Extensibility** by-design
- Present results in a **user-friendly** way.
- A **web application** to interactively present results



Currently supports Qiskit State Vector (with and without GPU), Cirq and PennyLane

Synergies with other sciences

The ESA-CERN Joint Announcement at Phi-Week 2020



→ THE EUROPEAN SPACE AGENCY

Φ-lab

WE EXPLORE · WE INVEST · COMMUNITY AND COLLABORATIONS · FLAGSHIP PROGRAMMES · ABOUT · OUR PEOPLE · PUBLICATIONS · NEWS & EVENTS

AI enhanced Quantum Computing for Earth Observation

Φ-DEPARTMENT / Φ-LAB / EXPLORE / THE Φ-LAB EXPLORE OFFICE / AI ENHANCED QUANTUM COMPUTING FOR EARTH OBSERVATION

QC4EO is a recent Φ-lab initiative established in collaboration with CERN. Quantum computing has the potential to improve performance, decrease computational costs and solve previously intractable problems in EO by exploiting quantum phenomena such as superposition, entanglement and tunnelling.

The initiative involves creating a quantum capability in ESA-ESRIN (Frascati) which will have the ability to solve the most computational demanding Earth observation problems by using Quantum Computing to support programmes such as Destination Earth and Copernicus. This collaboration will be extended to link the CERN Quantum Technology Initiative, which was announced in June 2020 by the CERN Director General, Fabiola Gianotti. Through this partnership, ESA and CERN will create new synergies, building on their common experience in big data, data mining and pattern recognition.

Chang, Su Yeon et al.,
QTNML2021@NeurIPS2021

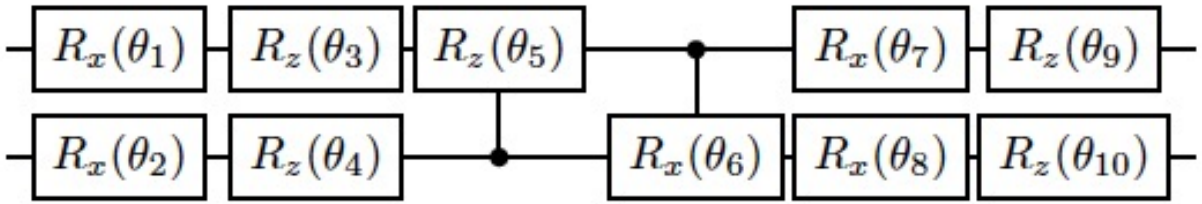
Quantum Convolutions

Convolutional Filters[1] as Parameterized Quantum Circuits (PQC) with single-qubit and two-qubit operations.

- Reduce risk of barren plateau

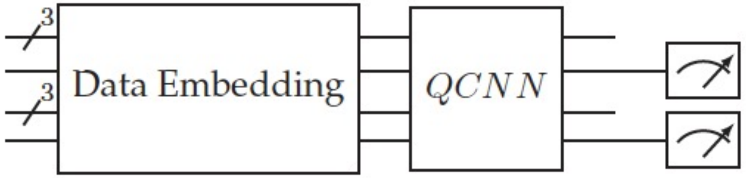
Alternative architecture: different parameters in each convolutional filters

- Increased model complexity and flexibility

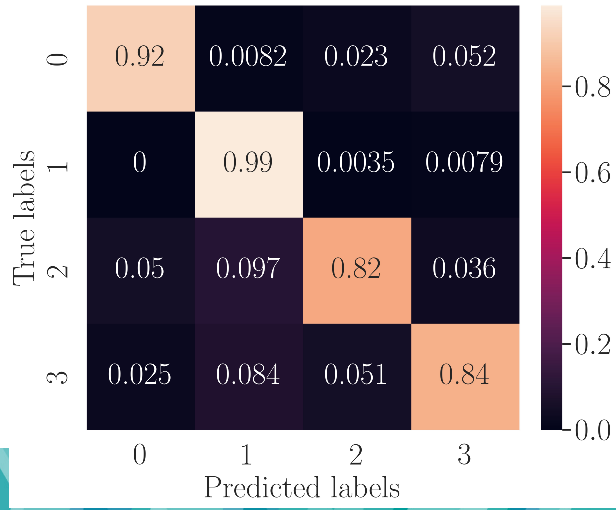


[1] T. Hur, L. Kim, and D. K. Park. Quantum convolutional neural network for classical data classification, 2021.

N-class classification by measuring the probability distribution for $\log_2 N$ qubit and using categorical cross entropy.



Confusion matrix of 4-class MNIST classification



Summary

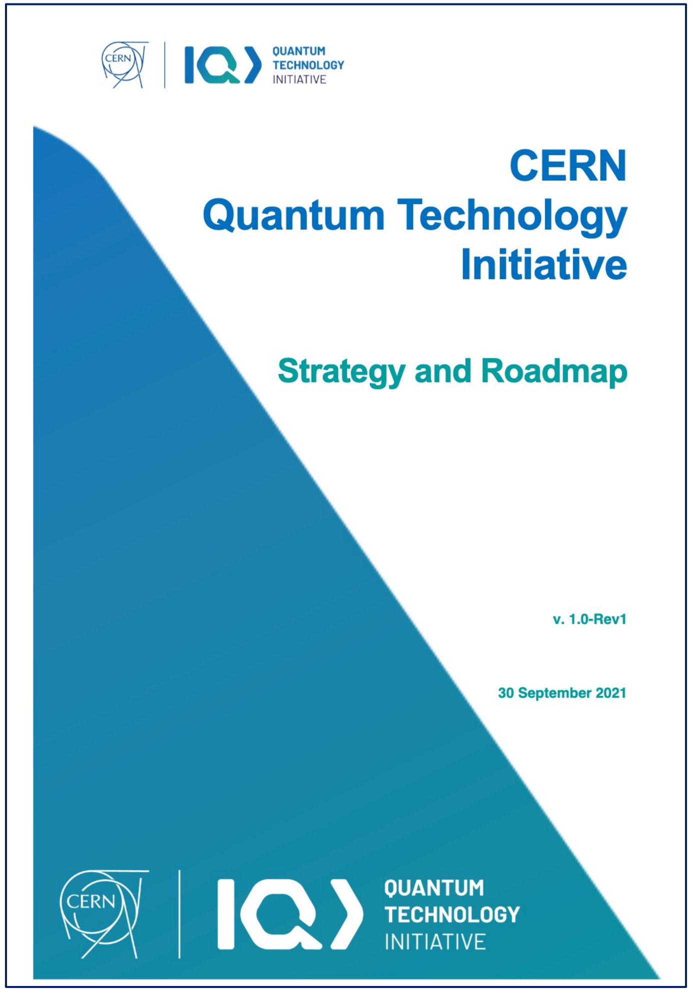
The QTI coordinates **quantum research at CERN**

Quantum Computing is a wide active area

Extensively investigating **QC and QML applications to HEP**

Setting in place **access to resources (classical and quantum)** to ease community R&D

Build **synergies and joint projects** beyond HEP



https://zenodo.org/record/5553775

Thanks!

Sofia.Vallecorsa@cern.ch