CERN QTI: unveils strategic roadmap shaping CERN’s role in next quantum revolution

Michele Grossi

CERN | QUANTUM TECHNOLOGY INITIATIVE

GPU Day 2021
The Future of Computing, Graphics and Data Analysis

Outline

- CERN: General Introduction
- CERN Quantum Technology Initiative
- CERN: Quantum Research Domain
- Classic and Quantum computing

CERN: General Introduction

CERN

"Science for peace"

1954: 12 Member States

- International organisation close to Geneva, straddling Swiss-French border, founded 1954
- Facilities for fundamental research in particle physics
- 23 member states,
  1.2 B CHF budget
- ~3'200 staff, fellows, trainees, …
- >13'000 associates

Members: Austria, Belgium, Bulgaria, Czech republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, United Kingdom
Candidate for membership: Cyprus, Estonia, Slovenia
Associate members: Croatia, India, Lithuania, Pakistan, Turkey, Ukraine
Observers: EC, Japan, JINR, Russia, UNESCO, United States of America
Numerous **non-member states with collaboration agreements**

>2'500 staff members, 645 fellows, 21 trainees

7'000 member states, 1'800 USA, 900 Russia, 270 Japan, …

Quantum Theory

pQCD and Standard Model — collider physics, parton showers, theory input for precision electroweak, interpretation of data from collision experiments

Heavy Ion — effective descriptions of quark gluon plasma, jets in heavy ion collisions, hydrodynamics of strongly coupled systems

Lattice — theory inputs for nuclear and particle physics, first principle calculations of the low energy aspects of QCD, lattice as a formal tool for understanding QFTS

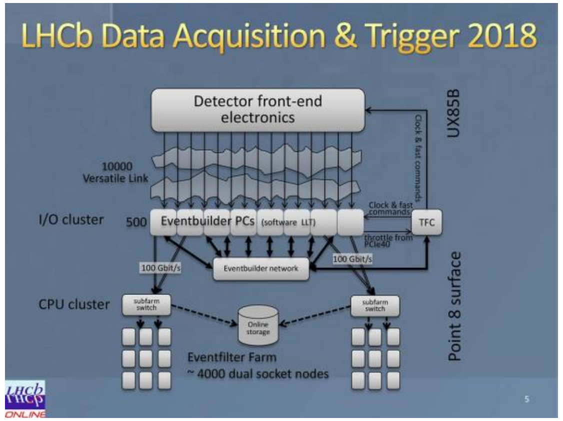
BSM — collider searches for BSM, dark matter model building, experimental signatures of dark matter, model building of new physics, BSM explanation of experimental anomalies

Strings/QFT — quantum gravity, string theory, conformal bootstrap, AdS/CFT correspondence, information paradox

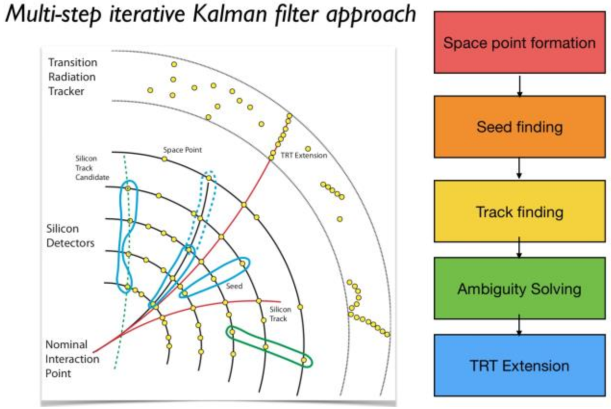
Cosmo/AstroParticle — properties and evolution of the early universe, large scale structure, dark sectors, neutrinos, gravitational waves, CMB

LHC Experiments Computing Workloads

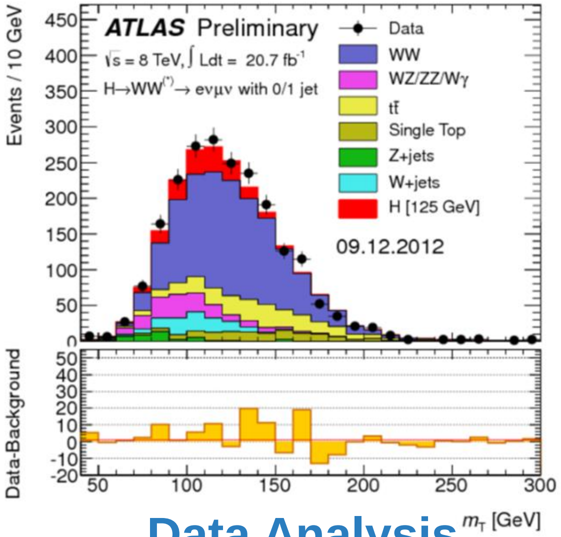
© Niko Neufeld - LHCb



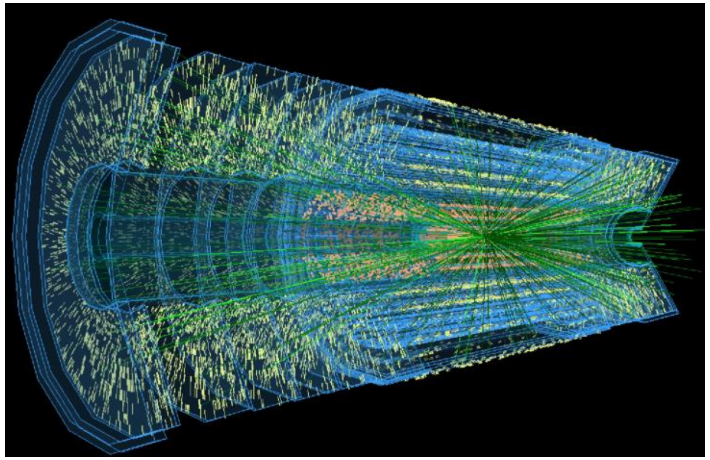
Data Acquisition



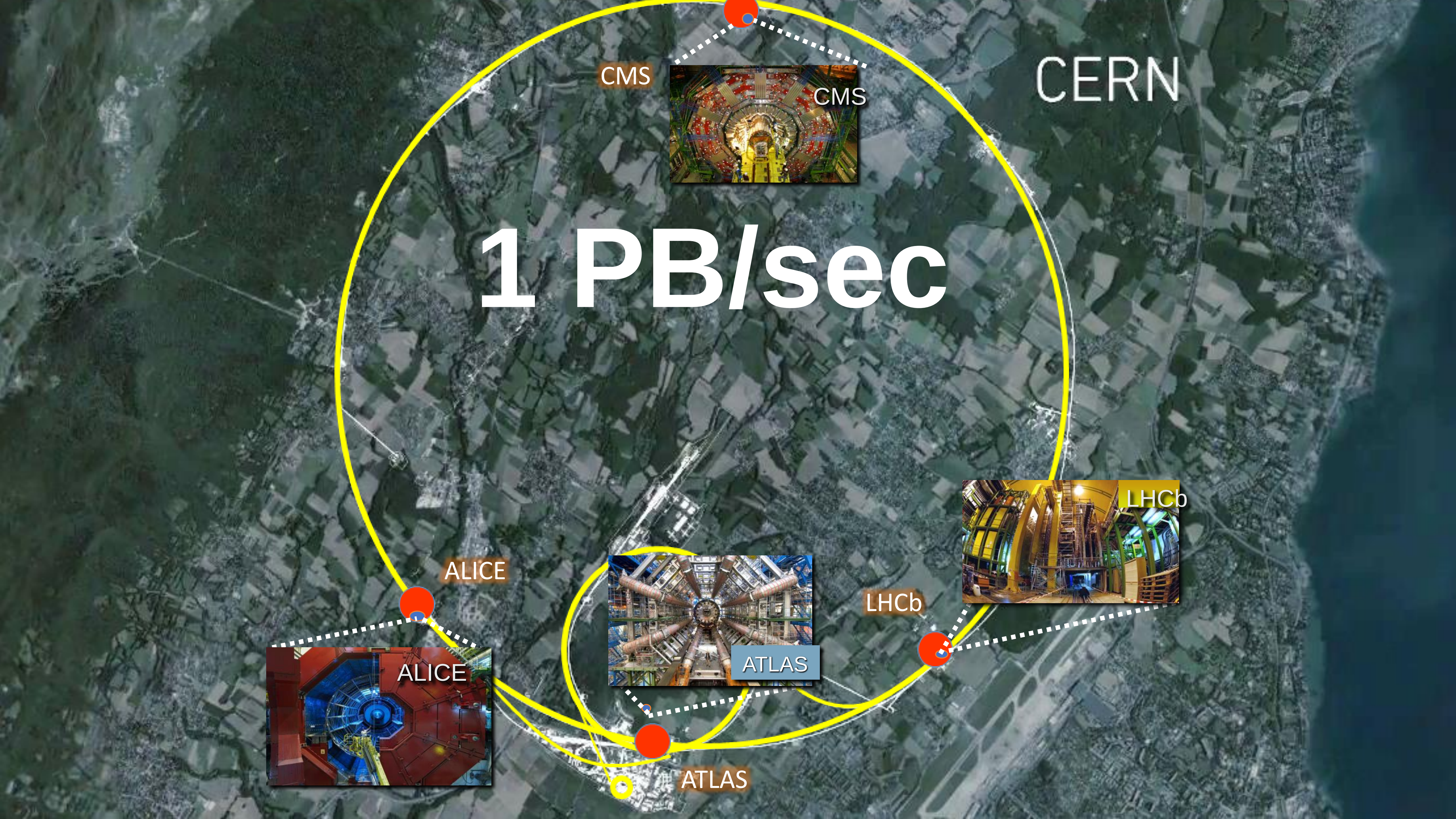
Track Reconstruction



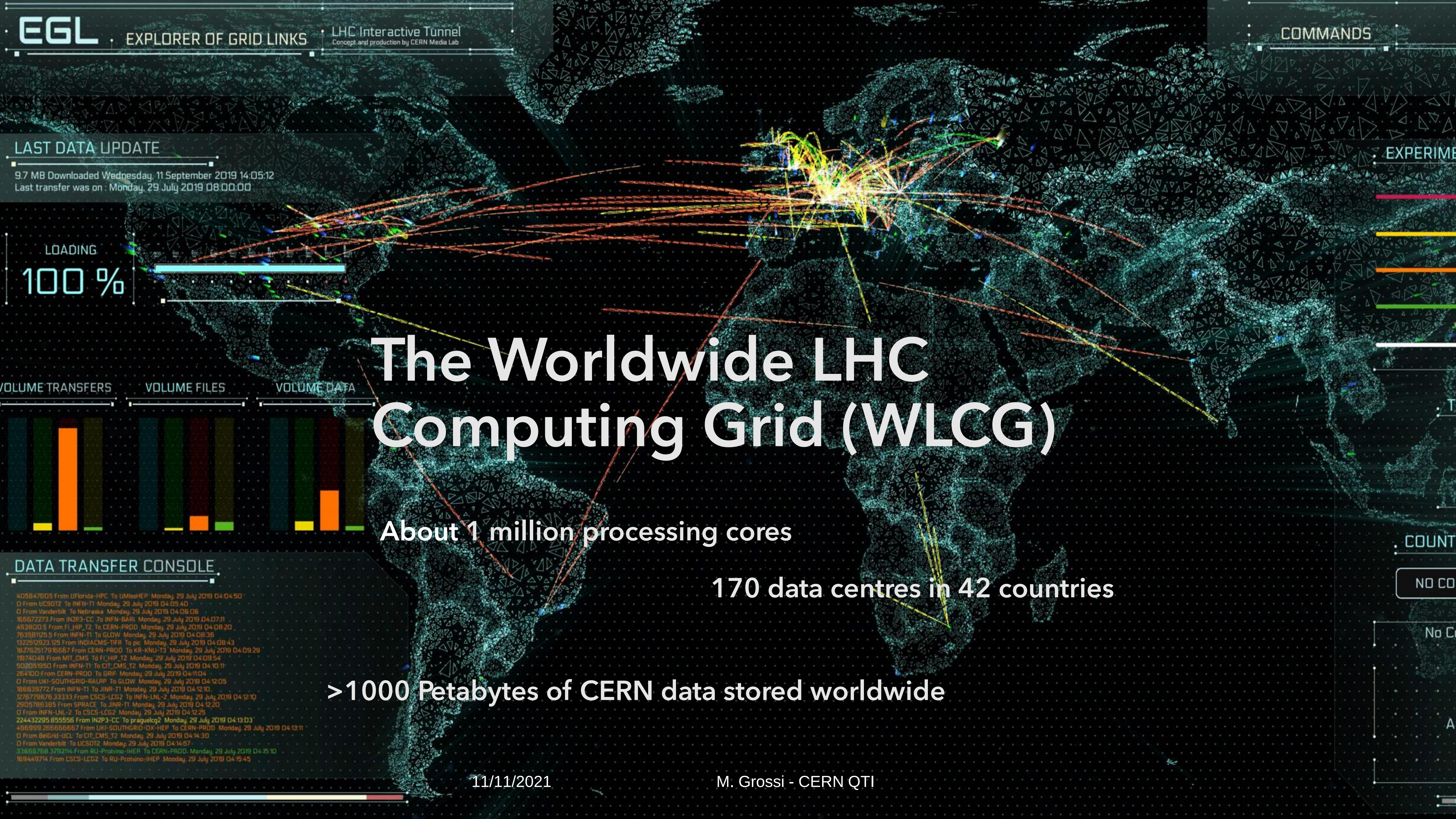
Data Analysis



Simulation



CERN
1 PB/sec
CMS
CMS
ALICE
ALICE
ATLAS
ATLAS
LHCb
LHCb



The Worldwide LHC Computing Grid (WLCG)

About 1 million processing cores

170 data centres in 42 countries

>1000 Petabytes of CERN data stored worldwide

CERN Quantum Technology Initiative

CERN Quantum Technology Initiative

Discussions about a Quantum Technology Initiative took place in 2020 with representatives of quantum initiatives in the CERN Member States, the CERN community, the Worldwide LHC Computing Grid, the CERN Scientific Computing Forum, with LHC experiments and the HEP Software Foundation


QUANTUM TECHNOLOGY INITIATIVE

CERN
Quantum Technology
Initiative

Strategy and Roadmap

v. 0.4-Rev3

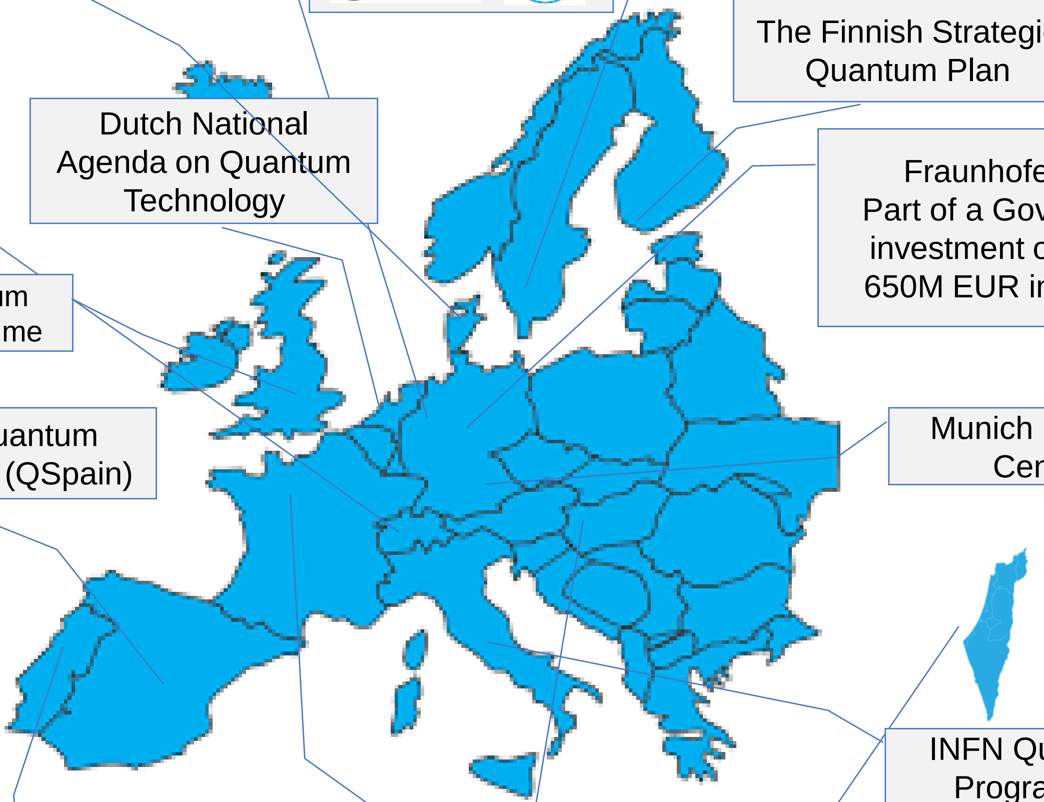
15 September 2021

QUANTUM TECHNOLOGY INITIATIVE

T1 - Scientific and Technical Development and Capacity Building	T3 - Community Building
T2 - Co-development	T4 - Integration with national and international initiatives and programmes

Member States Initiatives

- Many initiatives involving research labs, universities, companies have been announced in recent years
- National initiatives are put in place independently in several countries
- Companies have established large expertise networks: e.g. the IBM Quantum Network or Q-Net (with more than 100 members, many of them in Europe), or the Atos User Club
- Opportunities for joint collaborations and common programmes are emerging in particular in the CERN Member States



The QTI Advisory Board

1. A close relation with CERN Member States and ongoing activities is recognized as a fundamental key of success for the QTI

2. The establishment of an Advisory Board composed of qualified experts from the Member States has been strongly encouraged and supported by CERN Management and the CERN Council

3. The CERN Council Members have therefore been consulted and invited in January 2021 to propose candidates for the AB to represent each State

Who we are talking to

Organizations and Projects

QUANTUM FLAGSHIP

QuantHEP

esa

Industry

Google

IBM

IBM Q-Net

intel

aws

Amazon Braket

Microsoft

Xanadu

Atos

PASQAL

CQC Cambridge Quantum Computing

DESY.

EPFL

ETH zürich

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

lrz

TUM

INFN Istituto Nazionale di Fisica Nucleare

cnrs IN2P3

iit ISTITUTO ITALIANO DI TECNOLOGIA

QuTech

Universidad de Oviedo

Academia, Research Labs and Agencies

ICEPP The University of Tokyo

Fermilab

OAK RIDGE National Laboratory

CERN: a Quantum HUB

CERN Quantum Hub

CERN is a Hub Member of the IBM Quantum Network

Access to IBM hardware based on quotas for Hub members and projects

Agreement for 3 years at negotiated conditions

- All members have the same conditions as CERN

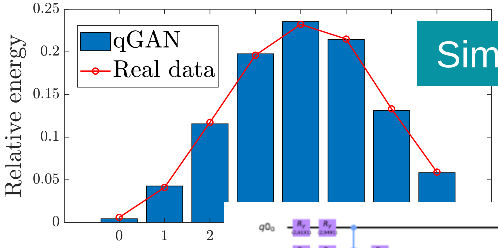
Now looking for expressions of interest for new members either for individual membership or projects (currently in discussion with a few institutes in the CERN Member States)

CERN Quantum Research Domains

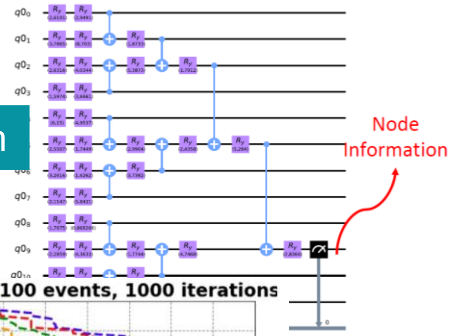
R&D Projects

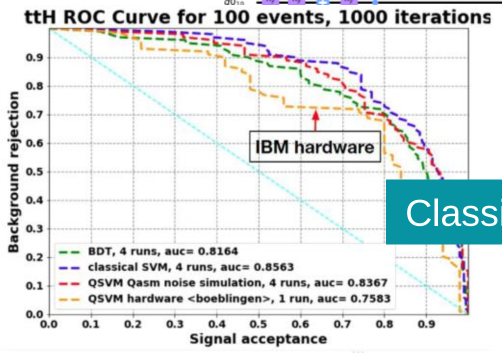
Computing

Simulation



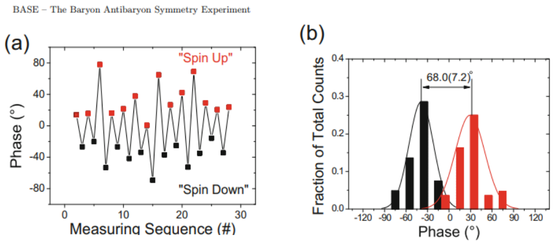
Reconstruction





Classification

Sensing

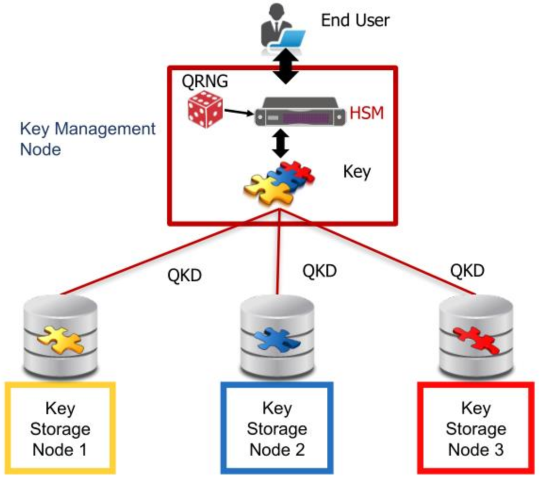


https://doi.org/10.1140/epjst/e2015-02607-4

Low-energy experiments, quantum states measurements, nano-technologies

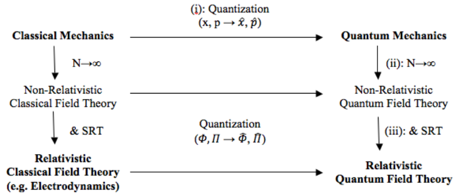
Future HEP Detectors

Communications

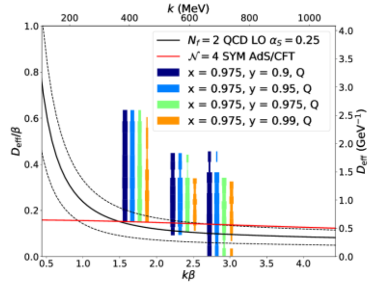


QKD infrastructures Quantum Internet

Theory



Quantum Field Theory



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

Lattice QCD

Many pilot projects already started as part of the **CERN openlab quantum** programme

Quantum Computing at CERN

- Assess **QC potential** in HEP
  - Development and optimization of algorithms targeted for **realistic** use cases
  - Ideal and NISQ configurations

- Build expertise on **state-of-the-art software stack**
  - Simulators, hardware specific vs agnostic frameworks, …
  - Optimisation of classical computing resources for QC studies (HPC)

- Set up a distributed QC **Simulation platform**
  - Provide **resource access** to the community for R&D

Initial investigations set a baseline for **prioritisation** and **systematisation**

- Start on **Quantum Machine Learning**
  - Relatively loose definition
  - Variational approach / Robustness to noise

Interest QC **algorithms beyond QML**

Now a **more formal approach** to algorithms, methods, error characterisation and correction

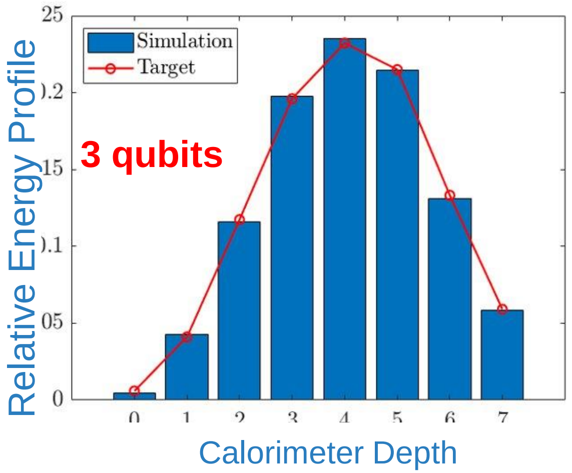
- NISQ optimisations
- Data embedding / scalability / problem dimensionality

Different hardware

- “Mainstream” (Semi-conductors, ions, …) (IBM, Google, Rigetti,IonQ)
- Photon QC (Xanadu) , Quantum Annealer (D-Wave)
- Quantum-inspired computing (Fujtsu digital, Toshiba SBM)

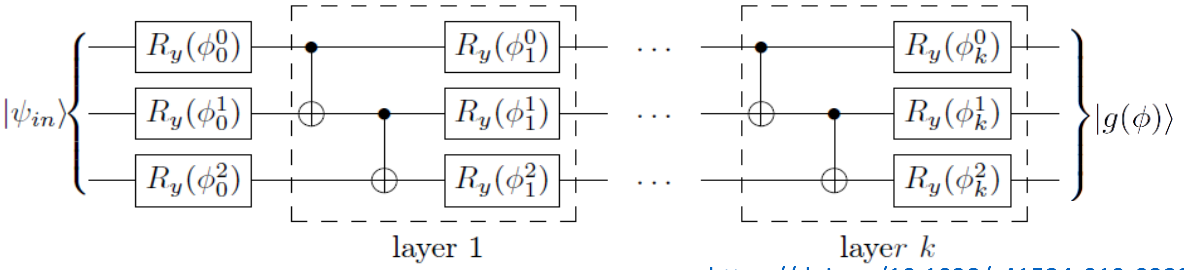
Hybrid Classical-Quantum GAN

IBM qGAN can load probability distributions in quantum states

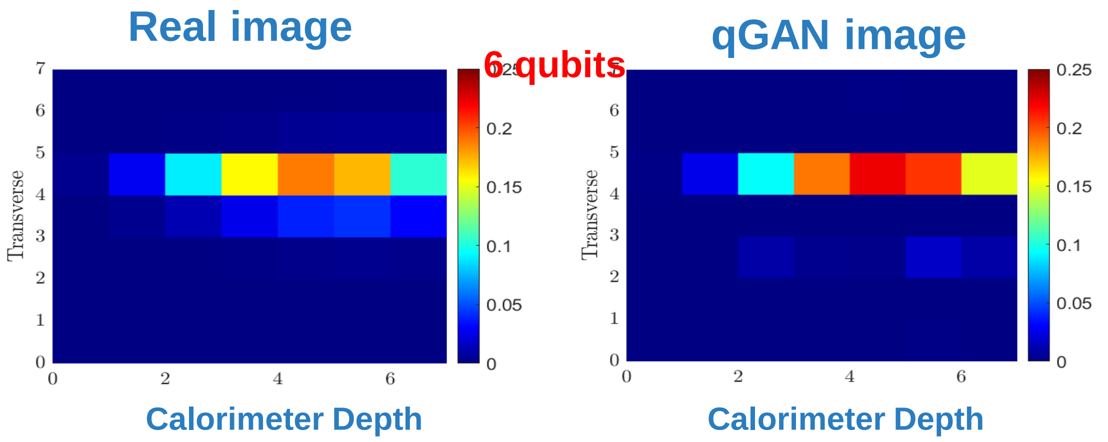


- 1D & 2D energy profiles from 3DGAN images
  - 2^n classical pixels expressed by n qubits
- Train a hybrid classical-quantum GAN to generate **average image**

Quantum Generator: 3 R_y layers



https://doi.org/10.1038/s41534-019-0223-2



Need a way to **sample single images**

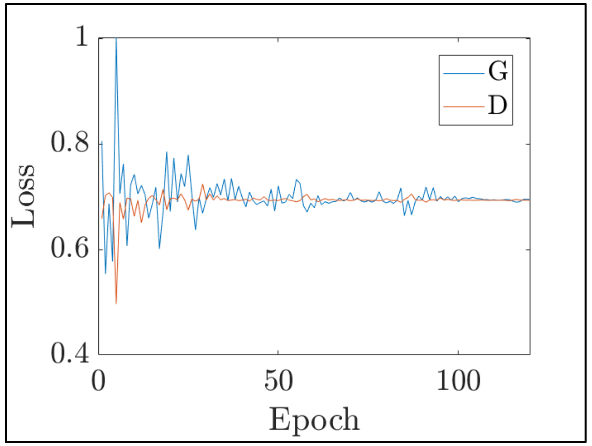
Photonic based qGAN

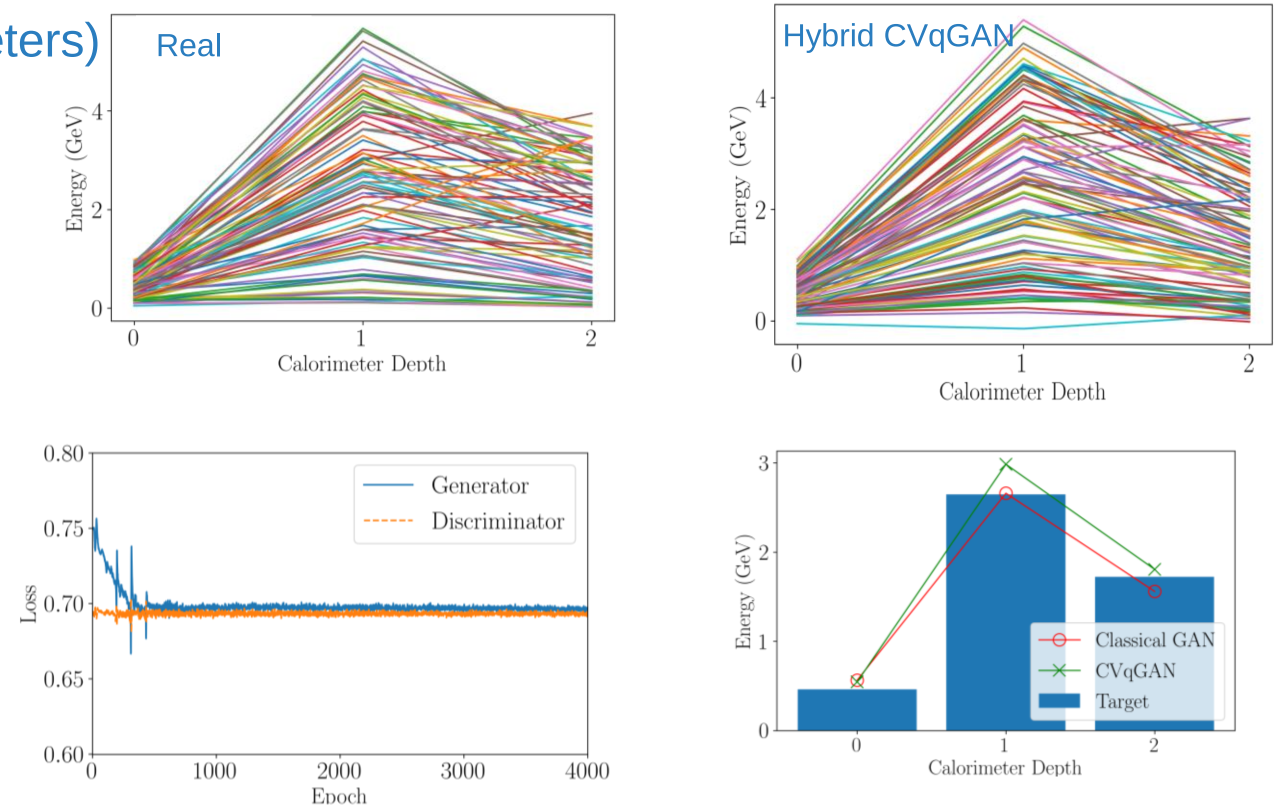
Alternative concept based on optical systems

Information encoded in continuous physical observables

Sofia Vallecorsa, CERN

- **Hybrid model**: 8 layers quantum generator (**264 parameters**)
- Fully connected classical discriminator (44k parameters)
- Converges in ~**100 epochs**
- **StrawberryFields + PennyLane** (Numpy backend)





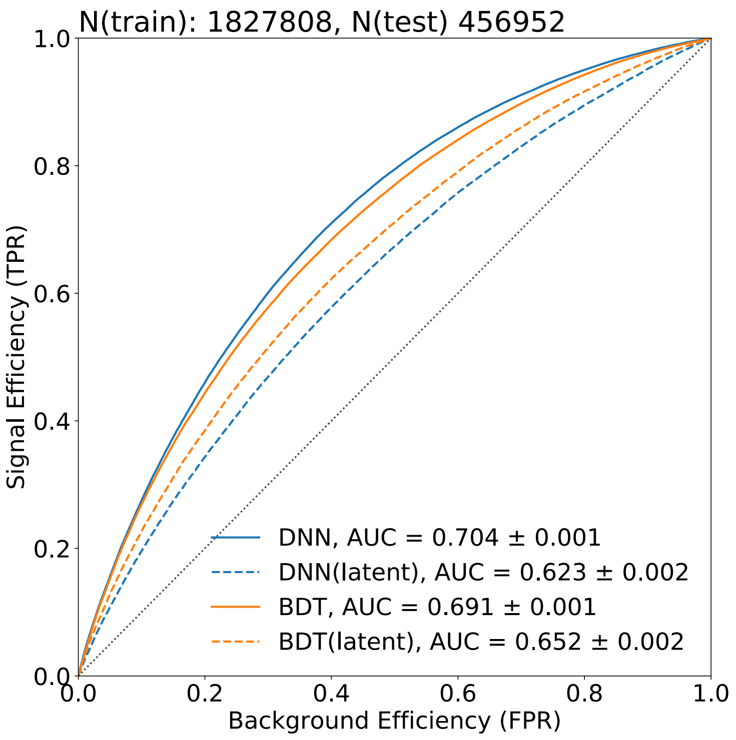
Classical GAN:
Fully connected generator (**44k parameters**)
Converges in ~**1000 epochs**

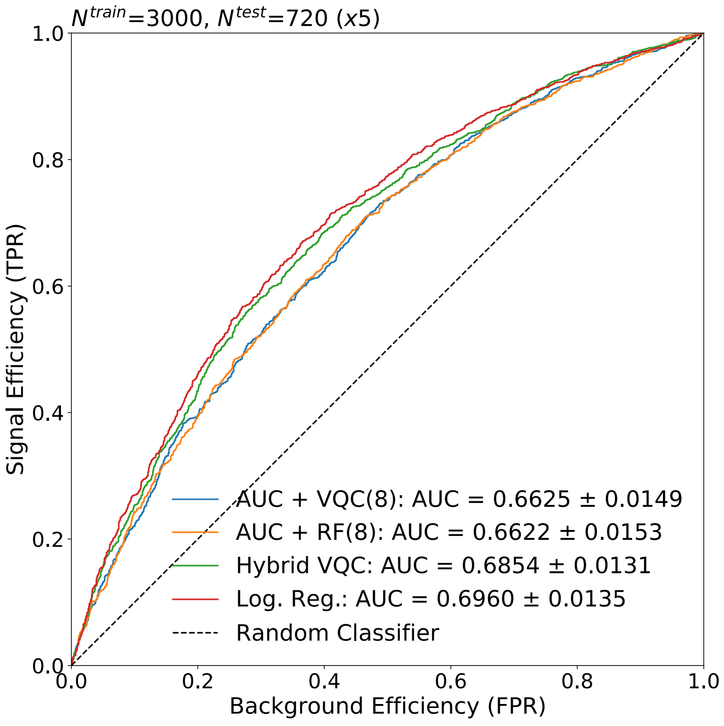
https://doi.org/10.1103/PhysRevLett.82.1784

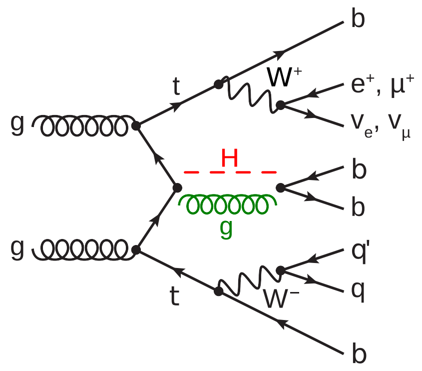
Quantum SVM for Higgs selection

Classical models trained on 67 features

Input dimensionality reduction: Auto-Encoder projects to a lower dimension latent space (8,16)







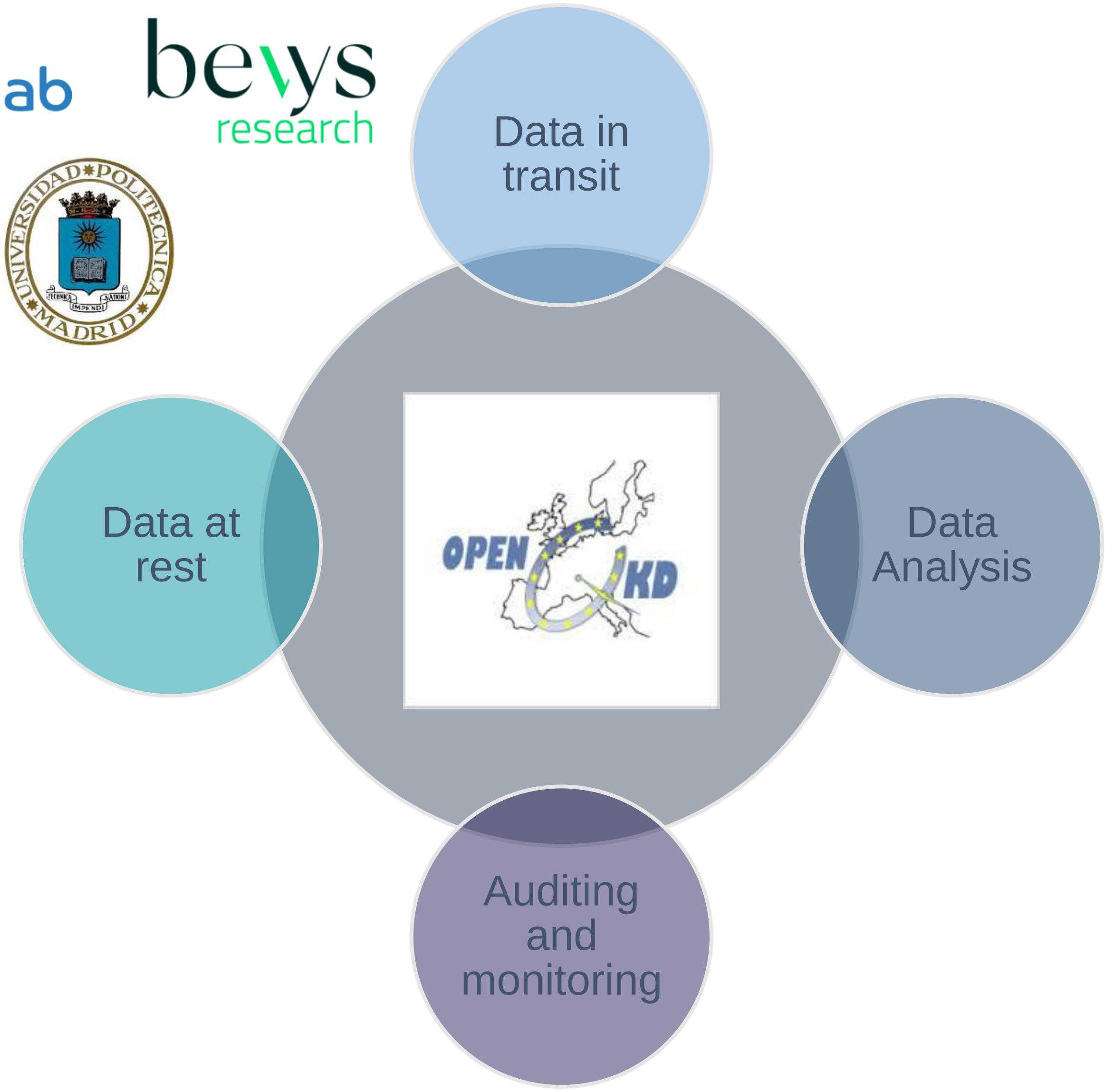
Feature selection + Model	AUC
AUC + QSVM	0.66 ± 0.01
PyTorch AE + QSVM	0.62 ± 0.03
AUC + SVM rbf	0.65 ± 0.01
PyTorch AE + SVM rbf	0.62 ± 0.02
KMeans + SVM rbf	0.61 ± 0.02

Feature selection + Model	AUC
AUC + QSVM	0.68 ± 0.02
AUC + Linear SVM	0.67 ± 0.02
Logistic Regression	0.68 ± 0.02

V. Belis, S. Gonzalez-Castillo - BQiT 2021
vCHEP2021
arXiv:2104.07692

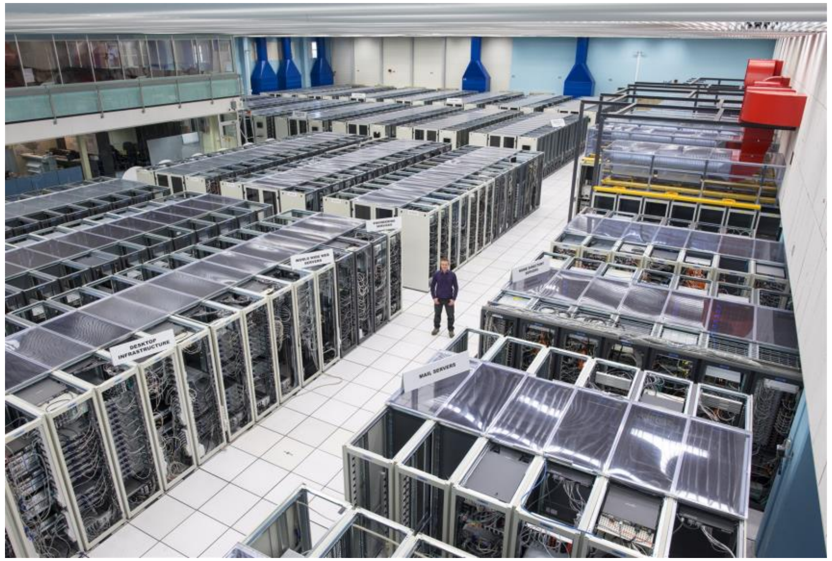
QUANTUMACY

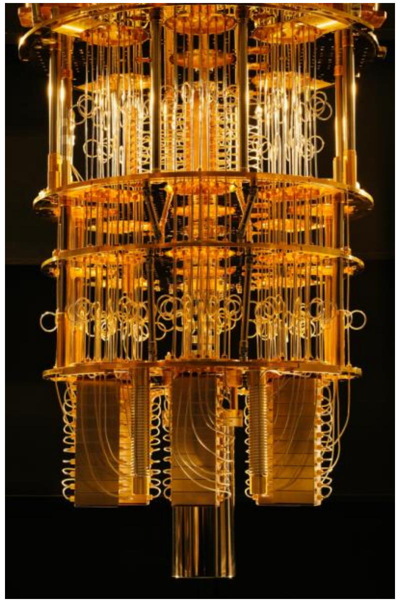
- **QUANTUM-based privacy and self-determination**
- Funded as an openQKD open call project
- End-to-end use of **QKD** to secure distributed data analysis over cloud infrastructures
- Data analysis: **quantum homomorphic encryption, SMPC**
- Auditing: **quantum block chains**
- **Medical use cases**: image classification and segmentation for neurological diseases research



CERN: Classic and Quantum Computing

Quantum and classical computing are complementary





Modern Infrastructure for Big Data & AI

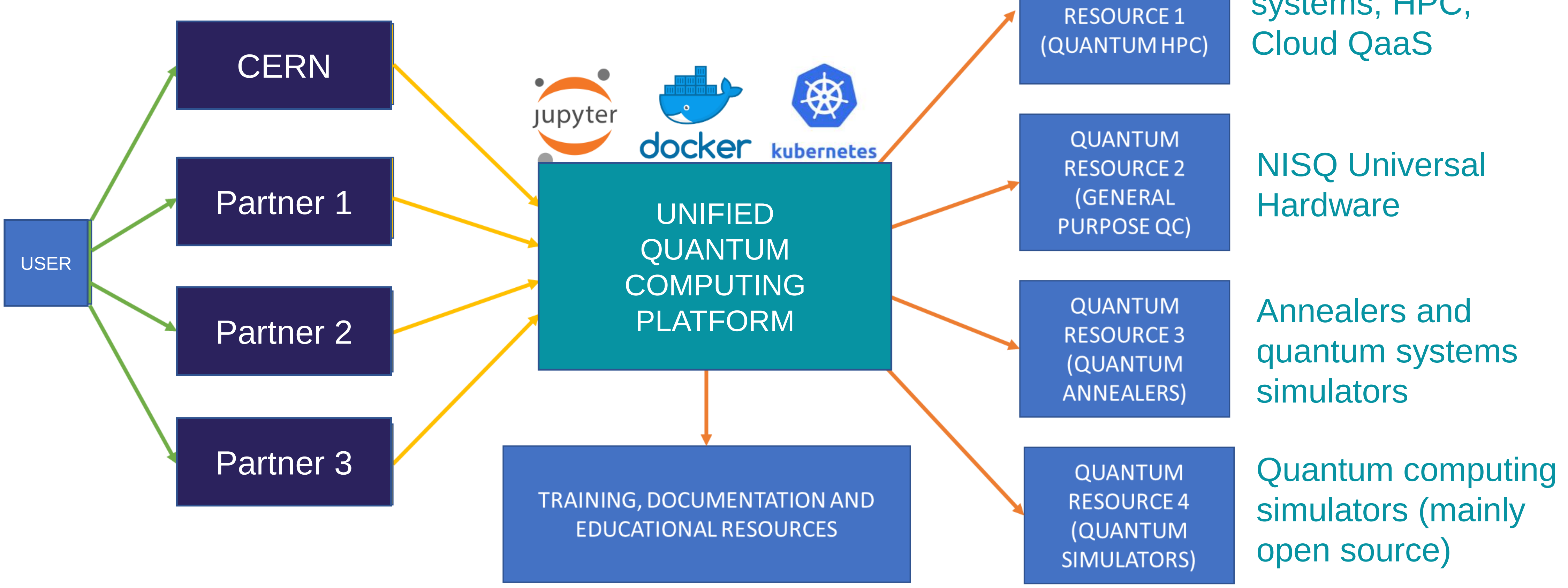
Store, manage and process huge quantities of data to extract insights and take business action.

Quantum Computers

Explore large set of possibilities and identify optimal answer to drive business value.

Quantum Computing Platforms

Goal to develop technologies and capacity in the CERN Member States



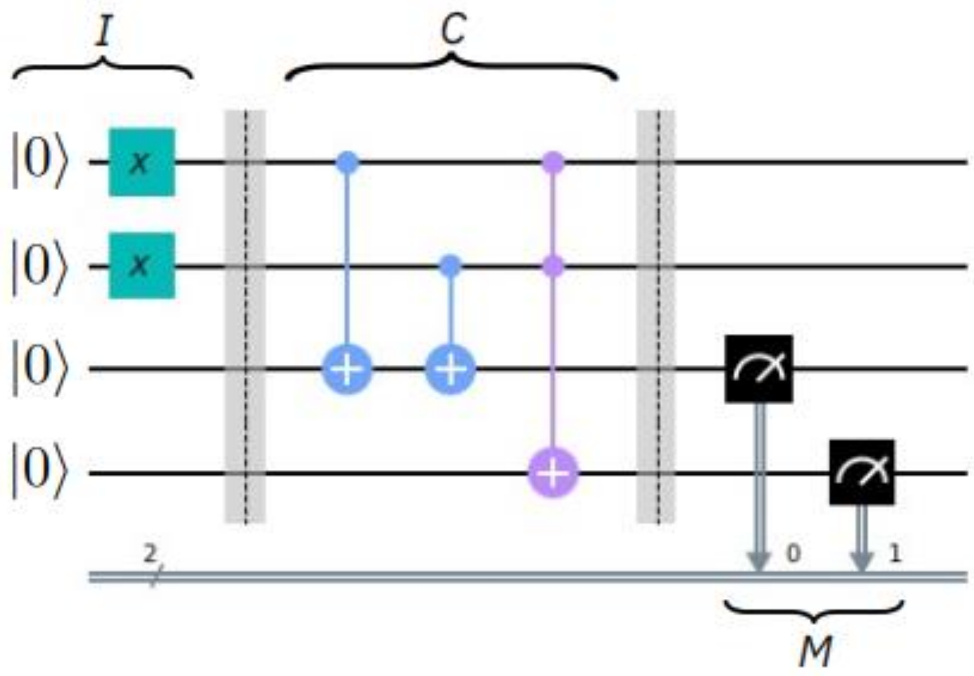
Challenges of Quantum Programming

- Qubits are analog
- Quantum programs result in probabilistic outputs
- You can’t read the entire exact state of a quantum program
- Each device (and qubit!) has characteristics a programmer has to be aware of, such as noise and connectivity
- Qubits have a short coherence time (or lifetime)
- There is no data input to a running quantum program

Simulating a Quantum Computer

Why and when to use simulator

- Prototype/understand quantum algorithms before running on a real device
- Simulation of large quantum systems is, in the general case, an exponentially hard computational task for a classical computer, *memory requirements double* for every qubit added
- *This in fact one of the main motivations for building a quantum computer in the first place!*
- For now, it's generally "cheaper" and "easier" to run an experiment, at least a small-scale one, on a simulator as compared to hardware
- In simulation we can understand noise properties of real devices and how noise affects performance (of e.g. algorithms)

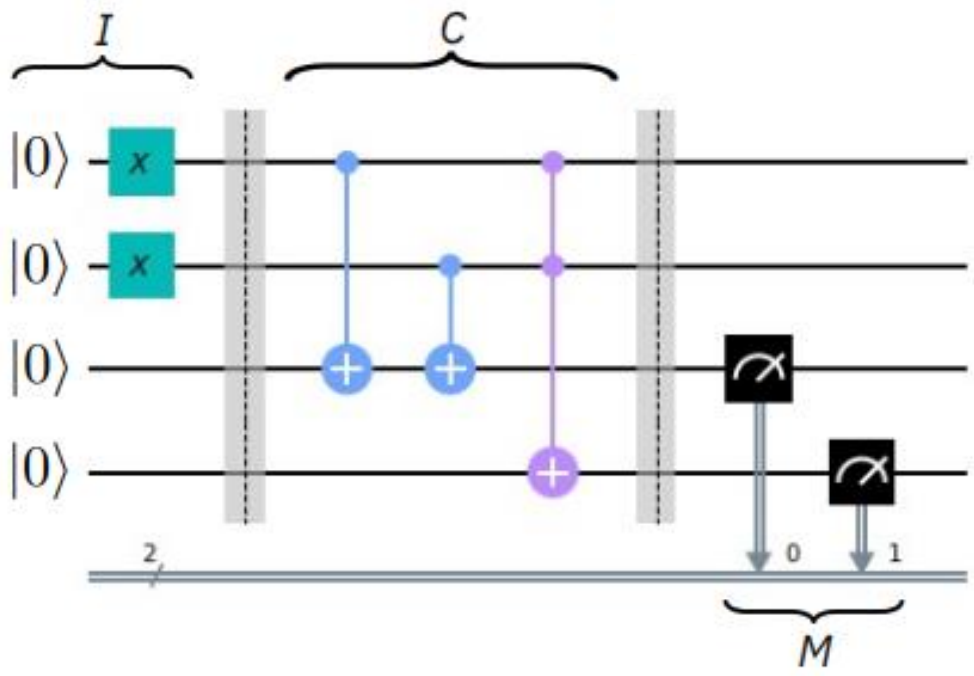


Simulating a Quantum Computer

Limits where classical simulation is "easy"

When simulating large quantum circuits is only polynomially hard:

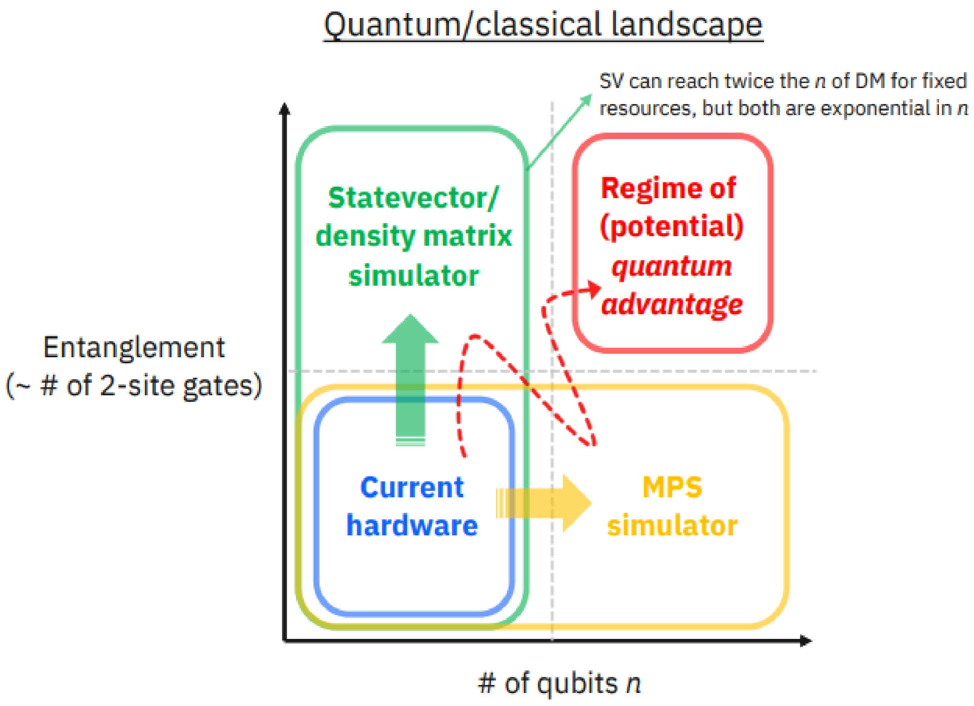
- tensor network with limited entanglement
- limited # of non-Clifford gate, scale polynomial in *n* and # of Clifford gates, but exponential in the # of non-Clifford gates



Simulating a Quantum Computer

We are getting to the point where experiments are being run which are difficult to simulate classically, e.g., 26 qubits, depth 60, 1000+ CNOTS with advanced error mitigation

- Kim et al., arXiv: 2108.09197

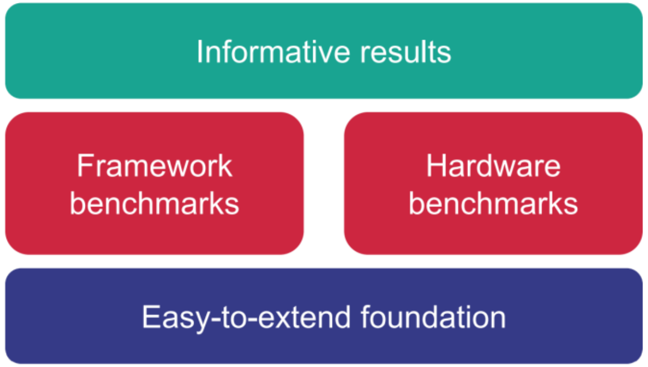


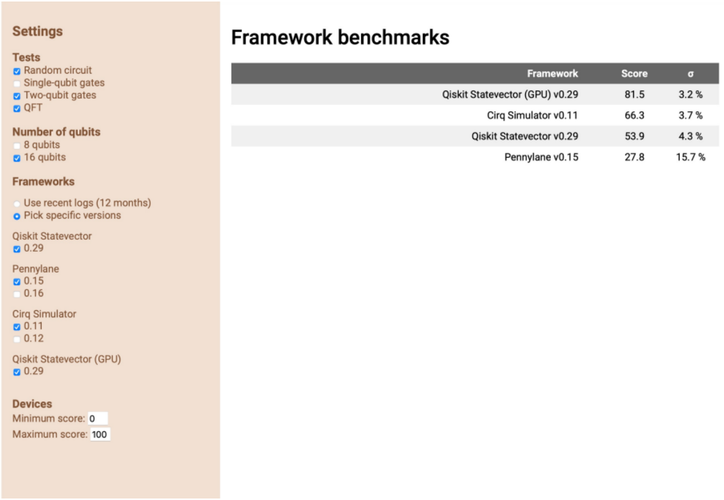
The ABAQUS Project

ABAQUS stands for Automated Benchmarking of Quantum Systems

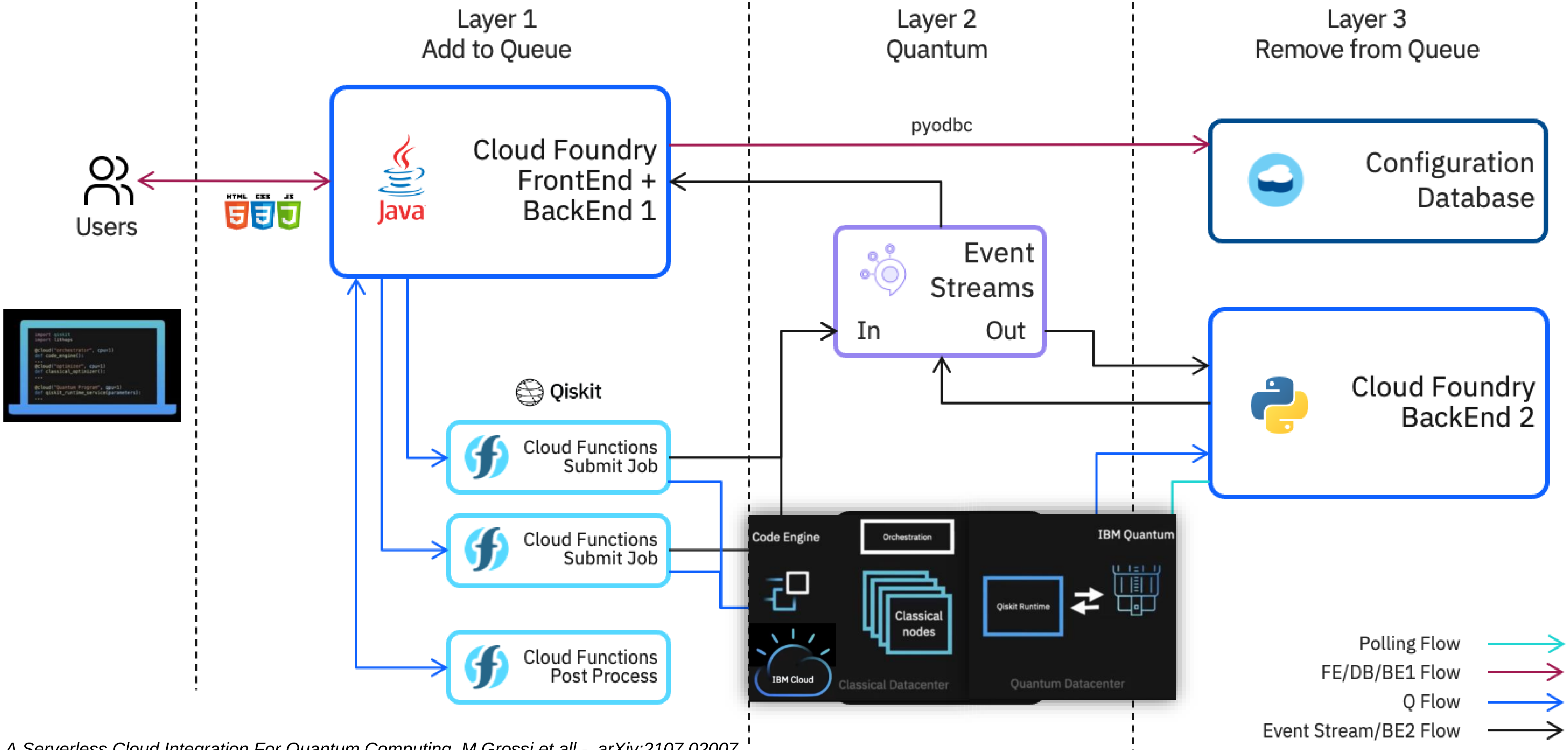
A collaborative platform for testing, assessing, extending, porting quantum algorithms across different architectures of quantum computing simulators and hardware

Support planned for different quantification approaches, including Quantum Volume, Q-Score, and others





Quantum Serverless Architecture



A Serverless Cloud Integration For Quantum Computing, M.Grossi et all - arXiv:2107.02007

Quantum Infrastructures

- CERN started the Web; we have some expertise it's in our DNA ☺
- CERN was part of early quantum networks experiments already 10+ years ago
- Interest in taking part in EU and international network deployment initiatives to build the future ***Quantum Infrastructures***
- Currently discussing with academic and commercial network and technology providers

Education Programme

Fundamental component to prepare the community for future applications of quantum technology

- Lectures and seminars with field experts (in collaboration with the CERN Academic Training Services)
- Training courses (in collaboration with academic and industry experts)
- Colloquia and specialistic seminars
- Hackathons
- Summer Students Programmes

CERN Accelerating science Sign in Directory

Quantum technology is an emerging field of physics and engineering that have the potential to revolutionise science and society in the next five to ten years. Knowledge in this rapidly evolving field has advanced considerably, yet still there are resources required that are not a mainstream today.

CERN can be at the forefront of this revolution. Given the broad range of specialised technical expertise found at CERN, the Laboratory is in a unique position today to take a leading role in the development of quantum technologies not only for its own programmes, but also as a general contribution to the advancement of science and technology.

The CERN Quantum Technology Initiative (QTI) will define a three-year roadmap and research programme in collaboration with the HEP and quantum-technology research communities. Together, we will establish joint research, educational and training activities, set up the supporting computing infrastructure, and provide dedicated mechanisms for exchange of both knowledge and technology.

LATEST NEWS



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