CERN

The CERN
Quantum Technology Initiative:

a Hub for Collaboration R&D in
Quantum Information Science and Technology

Alberto Di Meglio
CERN QTI Coordinator
CERN openlab
IT Department - CERN

13/01/2021

CERN Status and Mission

CERN

"Science for peace"

- 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

1954: 12 Member States

Members: Austria, Belgium, Bulgaria, Czech republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, 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**

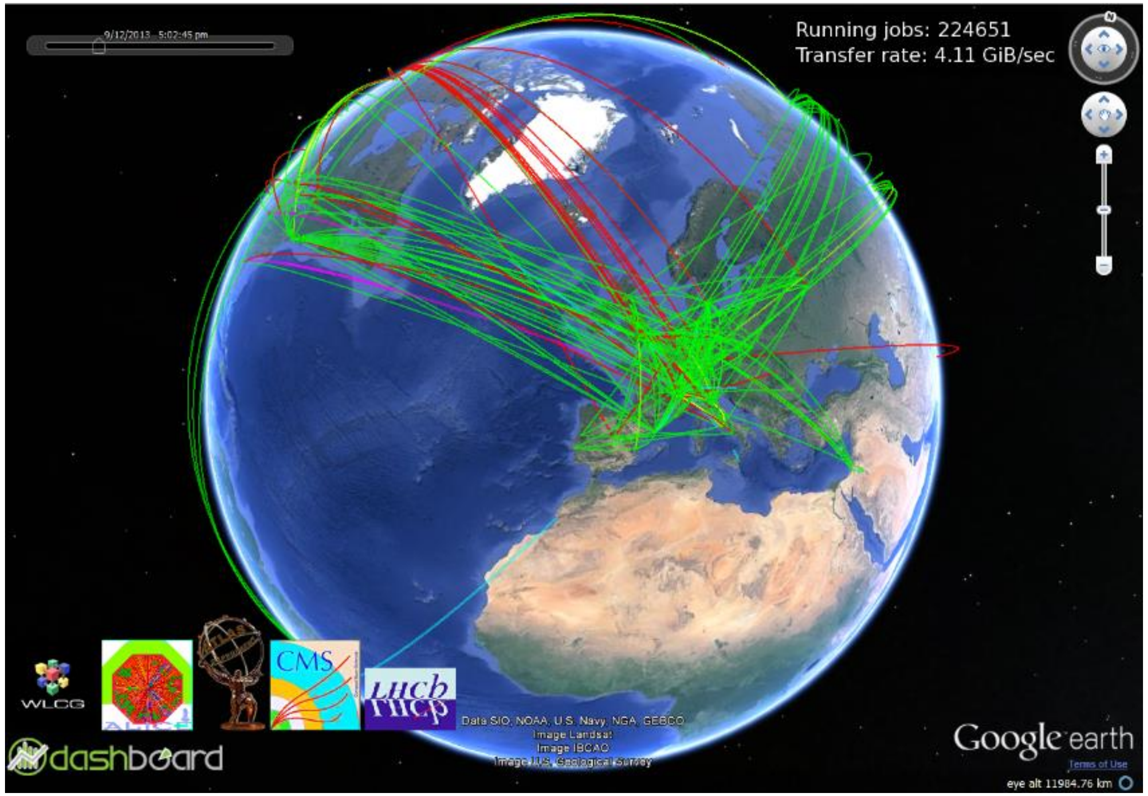
>2'500 staff members, 645 fellows, 21 trainees

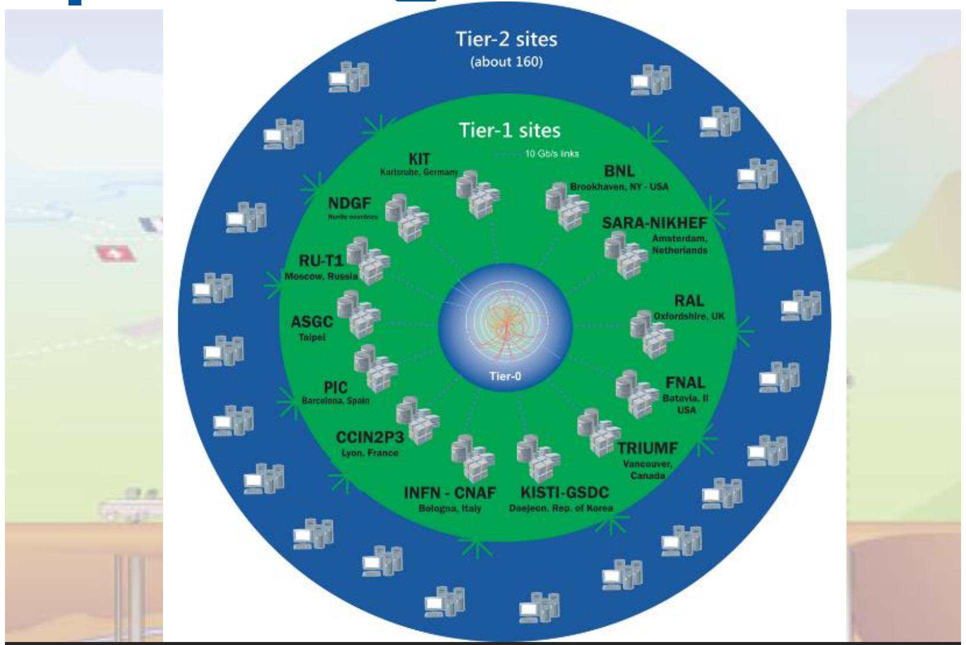
7'000 member states, 1'800 USA, 900 Russia, 270 Japan, …

CERN
QUANTUM TECHNOLOGY INITIATIVE

1 PB/sec
> 2000 disks/sec

Worldwide LHC Computing Grid





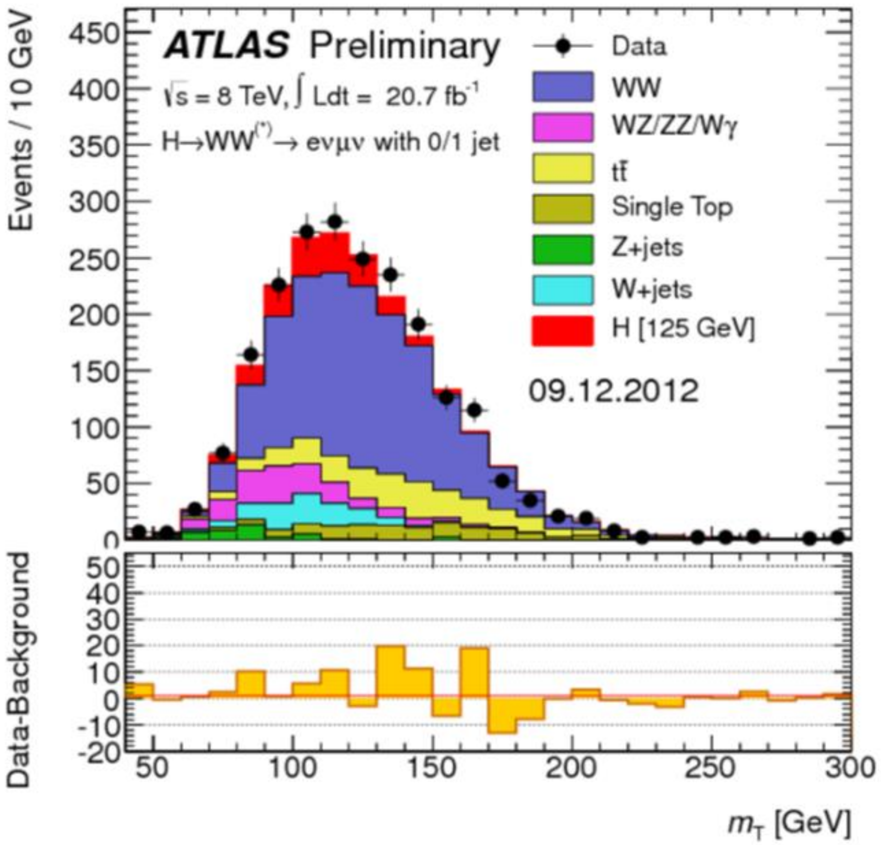
Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (13 centres):
- Permanent storage
- Re-processing
- Analysis

Tier-2 (42 Countries, ~170 centres):
- Simulation
- End-user analysis

- ~800,000 cores
- ~800 PB

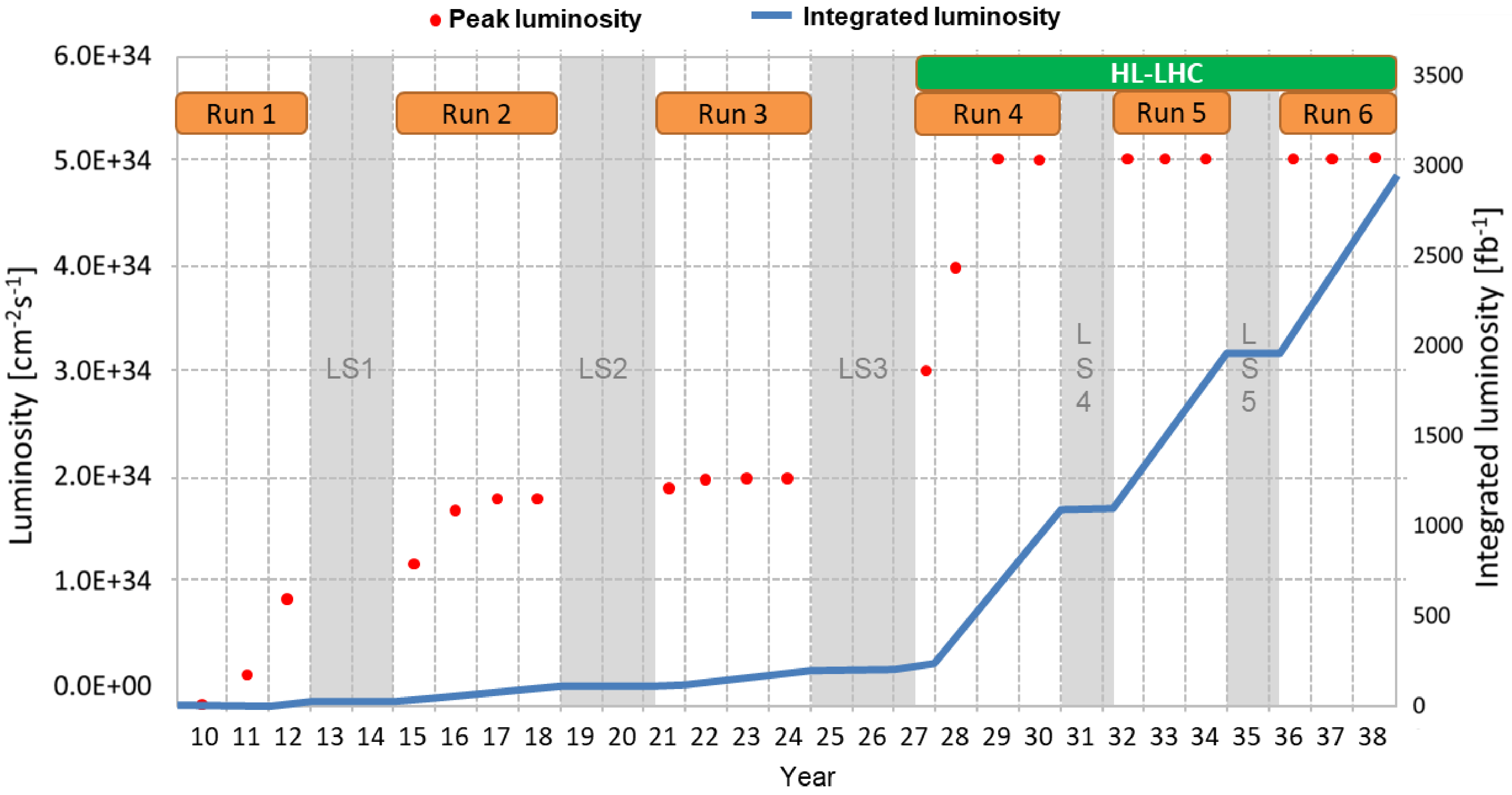
The Higgs Boson



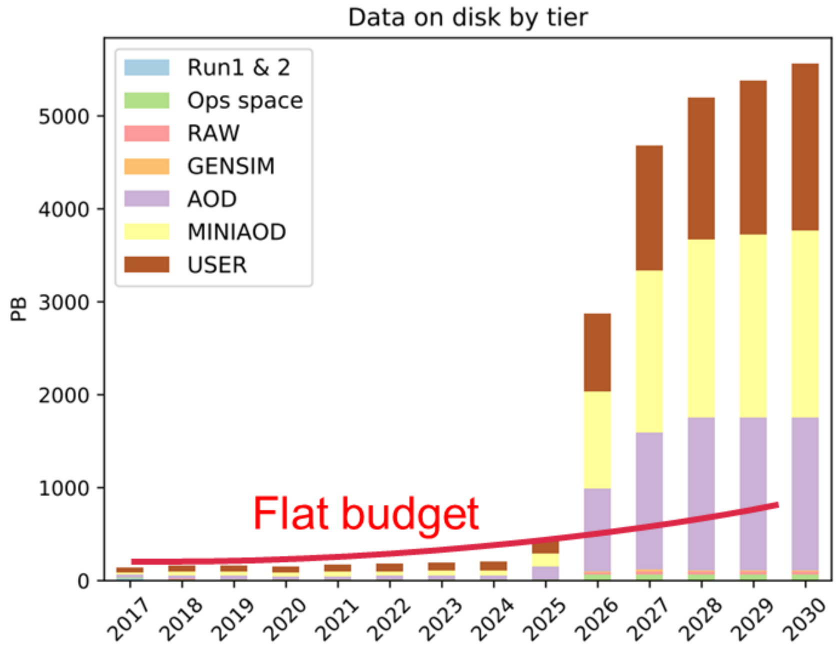
The Higgs Boson completes the Standard Model,
but the Model explains only about 5% of our Universe

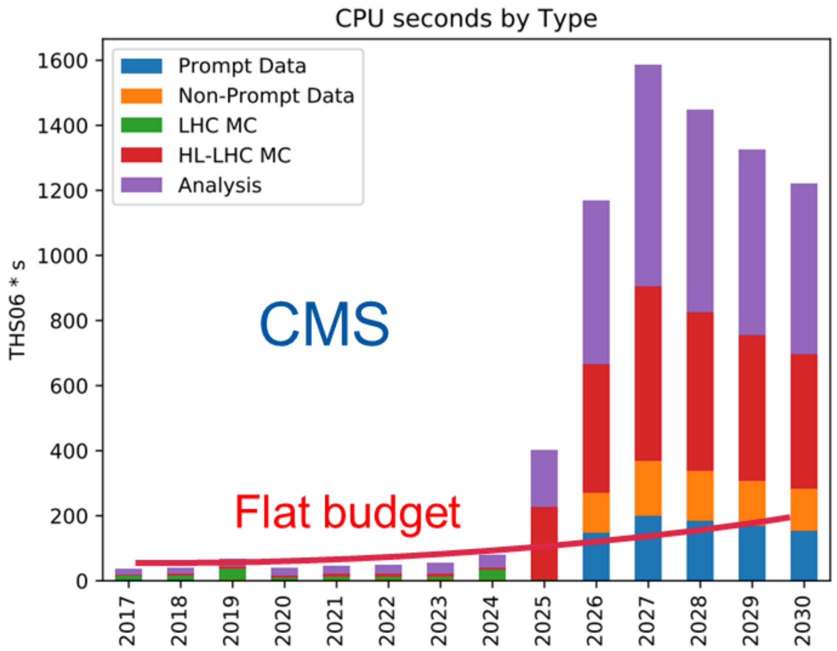
What is the other 95% of the Universe made of?
How does gravity really works?
Why there is no antimatter in nature?

LHC Schedule



Computing @ HL-LHC





https://arxiv.org/pdf/1712.06982.pdf

Raw data volume increases exponentially

- Processing and analysis load

Technology at ~20%/year will bring x6-10 in ~10 years

- Estimates of resource needs x10 above what is realistic to expect

Recommendations

Coming from all directions!

2020 Update of the European Strategy for Particle Physics

"the software and computing models used in particle physics research must evolve to meet the future needs of the field" and "the community must ***vigorously pursue common, coordinated R&D efforts in collaboration with other fields of science and industry, to develop software and computing infrastructures that exploit recent advances in information technology and data science****".*

HL-LHC Software and Computing Review Panel Report

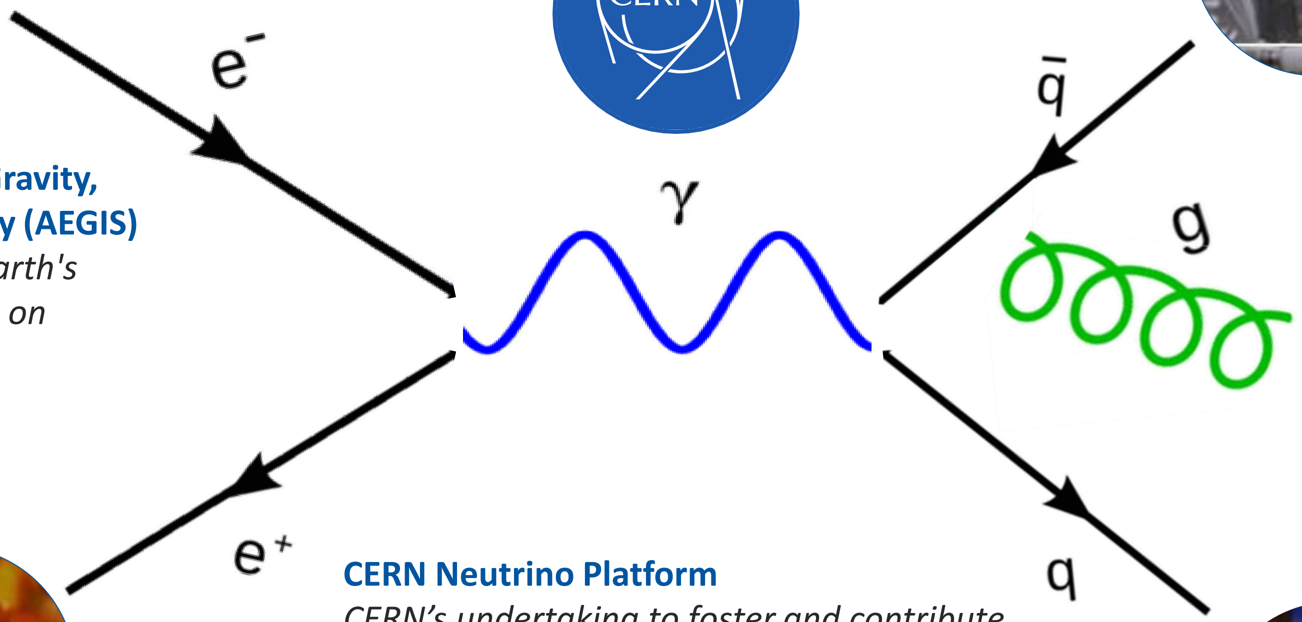
Highlights aspects such as improvement of code performance on hardware accelerator architectures or even the need to converge infrastructure projects to integrate in High Performance Computing (HPC) resources. It also highlights **that the LHC computing model must also consider the evolution of the international computing landscape**, such as the European Open Science Cloud (EOSC)

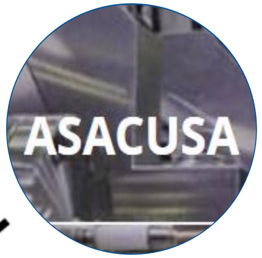
International HEP Strategy Roadmaps

The ongoing Snowmass process has already massively highlighted the need to focus on more integrated use of HPC, Clouds, ML/DL tools and frameworks, mainstream data analysis tools, **quantum technologies** and more

Non-LHC Experiments

Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy (AEGIS)
direct measurement of the Earth's gravitational acceleration, g, on antihydrogen.





Atomic Spectroscopy And Collisions Using Slow Antiprotons
studies the fundamental symmetries between matter and antimatter by precision spectroscopy of atoms containing an antiproton.

Antiproton Trap
compares protons with their antimatter equivalents.

ALPHA (successor of ATHENA)
makes, captures and studies atoms of antihydrogen and compares these with hydrogen atoms.

CERN Neutrino Platform
CERN's undertaking to foster and contribute to fundamental research in neutrino physics at particle accelerators worldwide

CERN Neutrino Platform

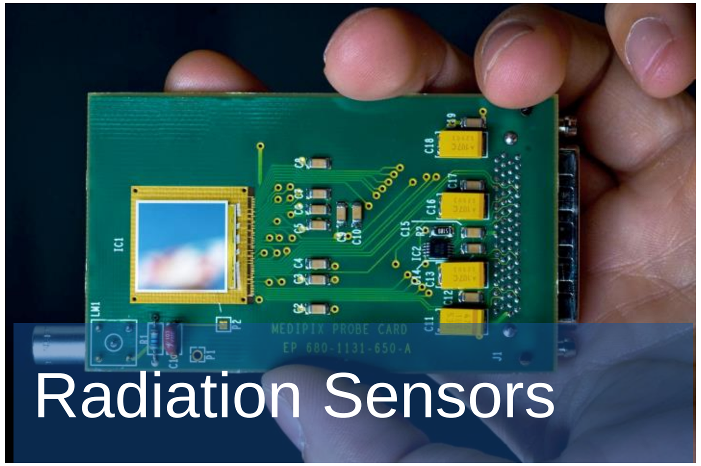
CERN Axion Solar Telescope
search for hypothetical "axions", proposed to explain why there is a subtle difference between matter and antimatter.

Engineering

Cryogenics

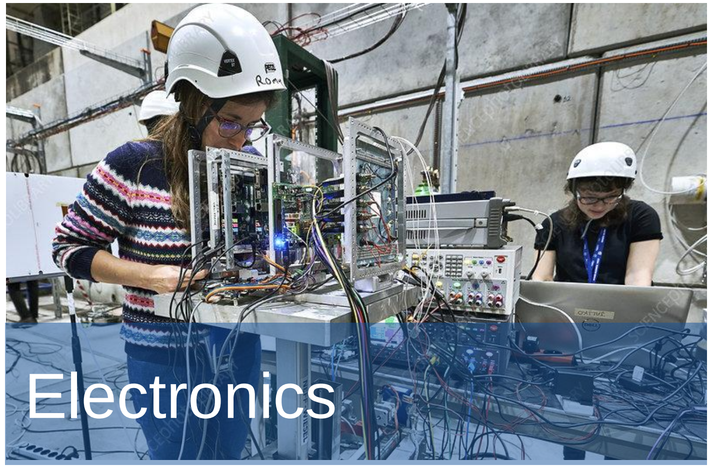
Vacuum

Mechanical Eng.
Material Science



Radiation Sensors

Lasers



Electronics

Theoretical Physics

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

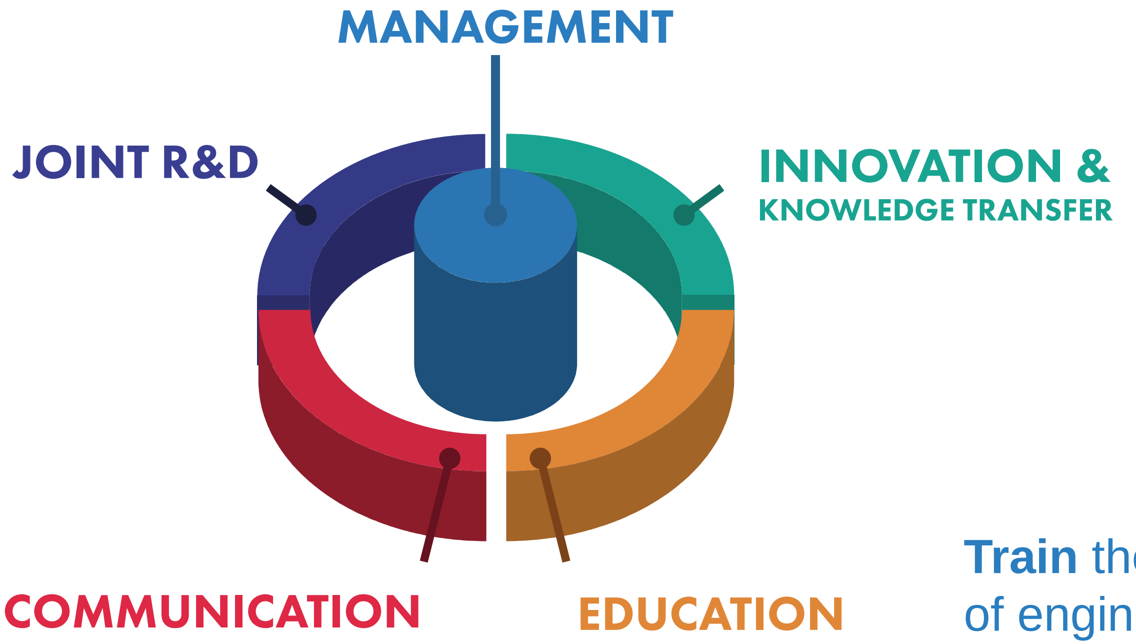
First Forays into Quantum Computing

CERN openlab

A Collaboration Hub for R&D in ICT and Computer Science

Evaluate and test state-of-the-art technologies in a challenging environment and improve them in collaboration with industry.

Collaborate and exchange ideas with other communities to create knowledge and innovation.



Communicate results, demostrate impact, and reach new audiences.

Train the next generation of engineers/researchers, **promote** education and cultural exchanges.

CERN openlab Phase VII

SET UP
2001

I
2003

II
2006

III
2009

IV
2012

V
2015

VI
2018

2021

Seventh Phase
VII

CERN openlab Collaboration Board 2017

JOINT R&D PROJECTS (PHASE VI)

Data Acquisition (LHCb, CMS, Dune, IT-CF)

High-bandwidth fabrics, accelerated platforms for data acquisition

Computing (EP-SFT, LHC Exp., OPL)

HPC, Cloud, Quantum

Cloud infra (IT-CM)

Cloud technology, containers, scalability

Data Storage (IT-ST, IT-DB, EP-DT)

Storage architectures, scalability, monitoring

Networks (IT-CS)

Software Defined Networks, Security

Control Systems (BE-ICS)

Predictive/proactive maintenance and operations

Data Analytics, Machine Learning (many)

Fast simulation, Data quality monitoring, anomaly detection, physics data reduction, benchmarking/scalability, systems biology and large-scale multi-disciplinary platforms

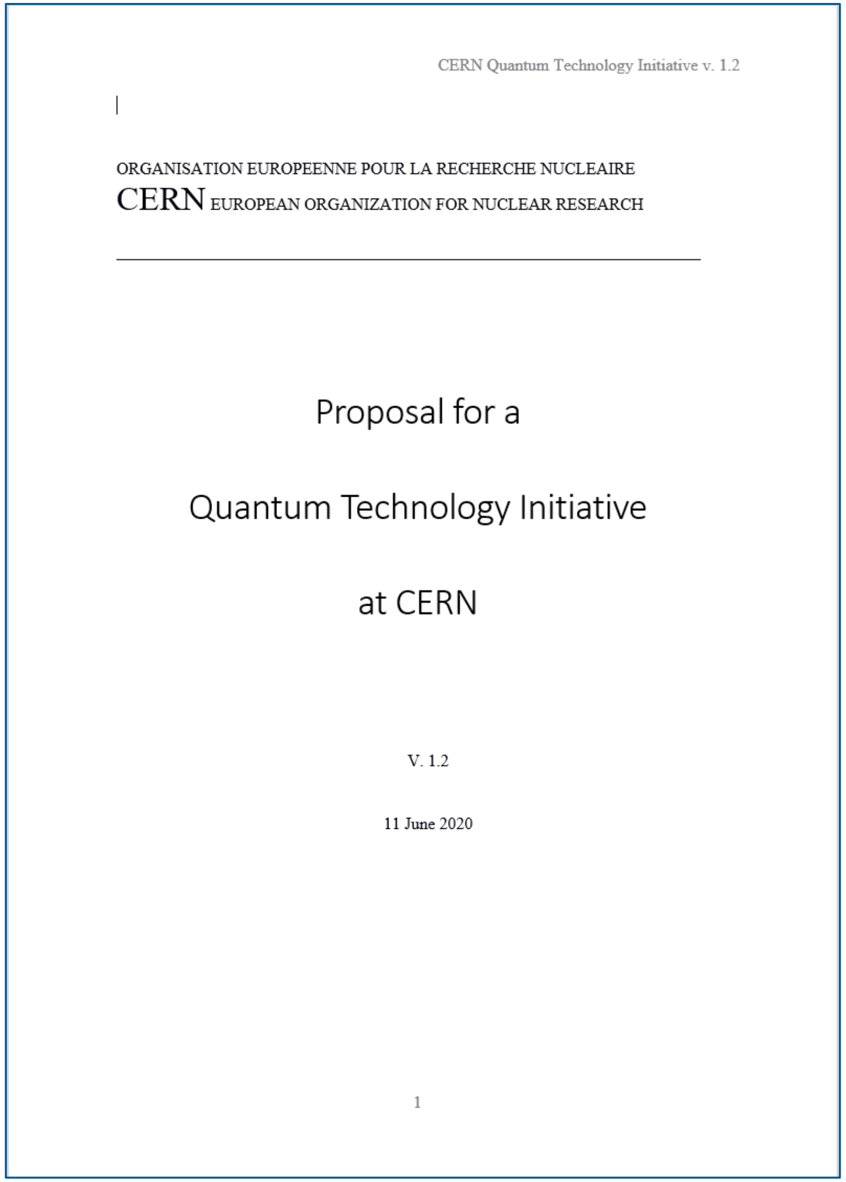
1^{st} CERN Quantum HEP Workshop

- CERN openlab has organized a kick-off event of its Quantum Computing initiative on **November 5^{th}-6^{th} , 2018**
  - https://indico.cern.ch/event/719844/
  - > 400 registered participants from the HEP physics community, companies and worldwide research laboratories and beyond
- Goals:
  - Create a database of QC projects to foster **collaborations** between interested **user groups, CERN openlab and industry**
  - Continue to seek **opportunities** to support QC projects
  - **Investigating ways of scaling up the QC activities**

The CERN Quantum Technology Initiative

Proposal

- Proposal defined by a Task Force across several CERN Departments, LHC Experiments and other CERN services
- Presented at the CERN Management and the CERN Scientific Policy Committee in June 2020
- Presented and approved by the CERN Council in September 2020


CERN Quantum Technology Initiative v. 1.2

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal for a

Quantum Technology Initiative

at CERN

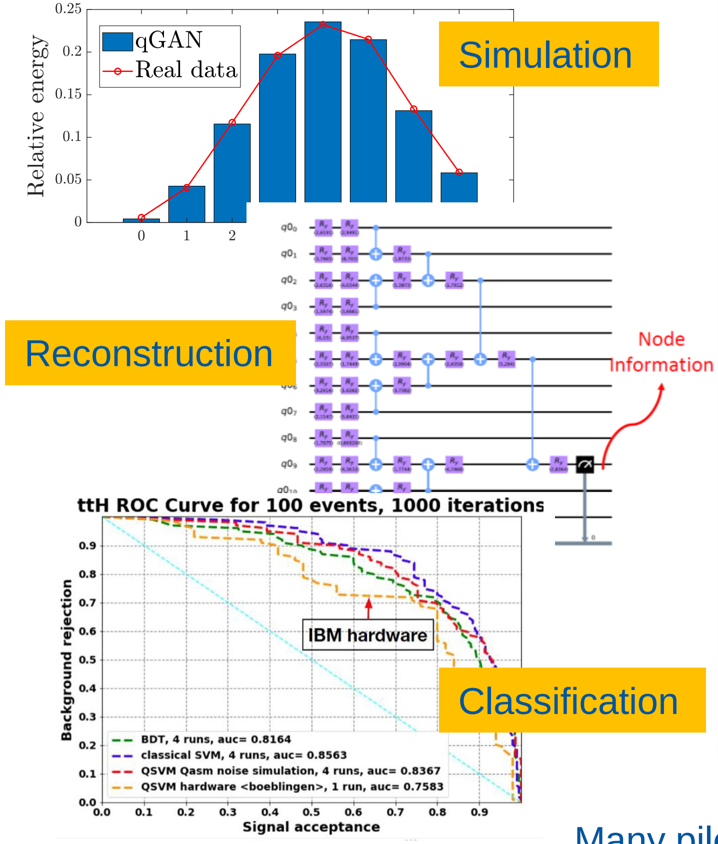
V. 1.2

11 June 2020

1

CERN Unique Expertise and Activities

Computing

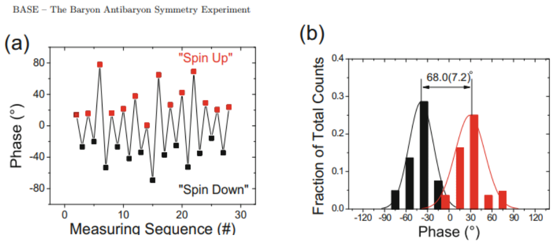


Simulation

Reconstruction

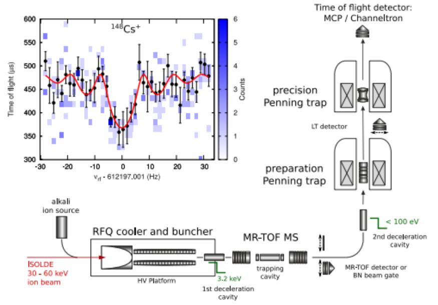
Classification

Sensing



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

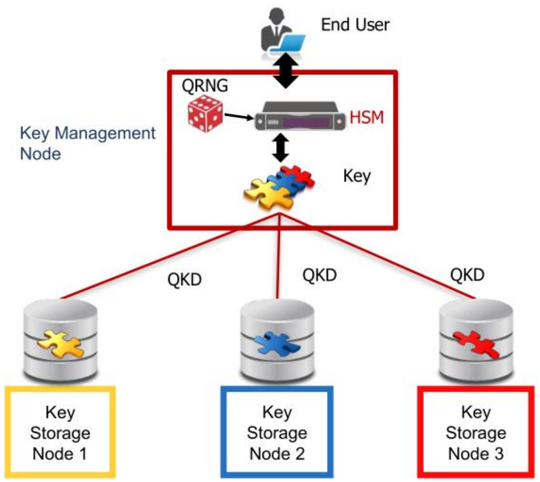
BASE phase-sensitive measurement of spin allowing very precise magnetic field drift measurements



https://doi.org/10.1088/1361-6471/aa5a20

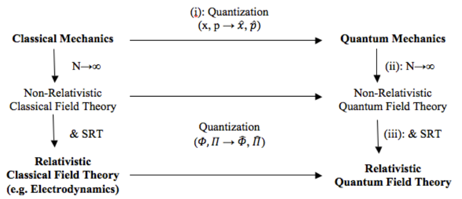
ISOLTRAP Mass-Spec

Communications

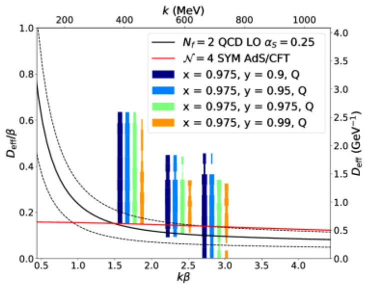


openQKD Repeater node in the CERN Data Centre

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 (https://openlab.cern/quantum)

Goals of the Initiative

Discussions about a Quantum Technology Initiative took place over the past 6-8 months 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

CERN is in the unique position of having in one place:

- The **diverse set of skills and technologies** necessary for multi-disciplinary endeavours like QT (software, computing and data science, theory, engineering, cryogenics, electronics, material science, and more)
- **Compelling use cases** pushing the boundary in a unique way and create ideal conditions to compare classic and quantum approaches and understand the potential of quantum advantage
- A rich **network of academic and industry relations** working on the state-of-the-art, unique collaboration models like **CERN openlab** (https://openlab.cern) bringing together the user expertise and interest and the aspiration of companies.
- The capacity to **produce and share innovation** for the further benefits of its Member States and act as a **hub of exchanges of expertise**

Objective 1: Strategy and long-term benefits

- Capitalize on CERN uniqueness, organize the different lines of R&D at CERN under a common initiative and vision and define a shared roadmap
- Assess the potential impact of quantum technologies on CERN and HEP research in the timescale of HL-LHC and beyond
- Build over time the required knowledge and capacity to turn the potential into realized impact

Objective 2: Implementation and execution

- Implement the above strategy by means of:
- A set of concrete R&D objectives in the four main areas of QT for the next 3 years
- An international academic, education, and training programme in collaboration with leading experts, universities and industry
- Mechanisms for knowledge sharing within the Member States, the HEP community, other scientific research communities and society at large

CERN Quantum Technology Initiative

Strategy


Joint HEP R&D Programme

CERN Management

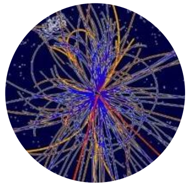

Advisory Board and QT Forum (**with large representation of the Member States**)

Coordination

QT Initiative Management

R&D


Sensing, Detectors R&D


Computing & Engineering


Communication


Simulation, Information Processing

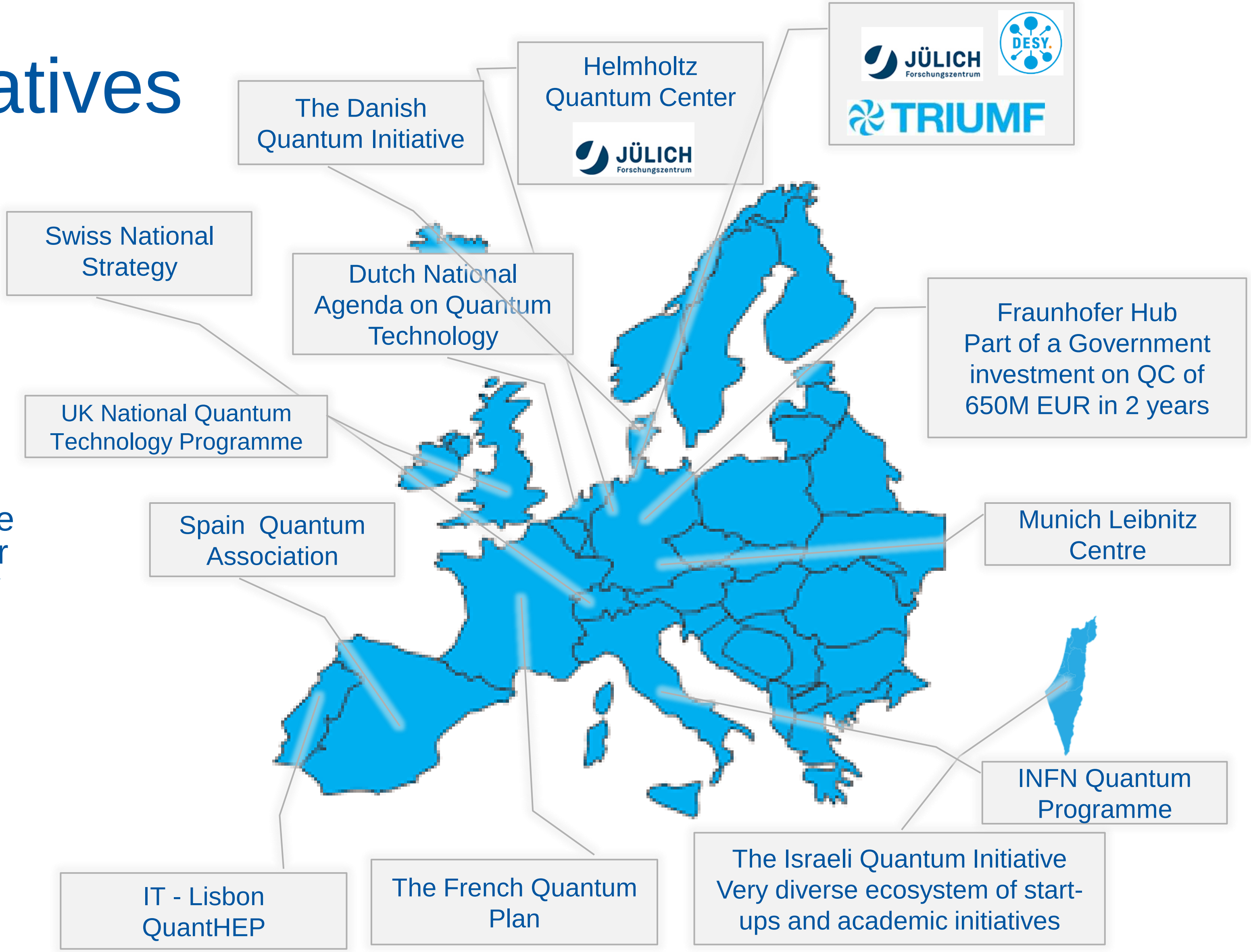
Capacity building

Academic Programmes / Industrial Collaborations

Collaborations

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



Worldwide Initiatives and Investments

Who we are talking to

Organizations and Projects

QUANTUM FLAGSHIP

QuantHEP

esa

Industry

Google

IBM Q-Net

intel

aws Amazon Braket

Atos

Cambridge Quantum Computing

Microsoft

DESY.

EPFL

ETH zürich

ICEPP The University of Tokyo

INFN Istituto Nazionale di Fisica Nucleare

Universitas Studiorum Insubriae

Orta Doğu Teknik Üniversitesi Kuzey Kıbrıs Kampusu – Middle East Technical University Northern Cyprus Campus

Universidad de Oviedo

Universitas Studii Paduani

University of Waterloo

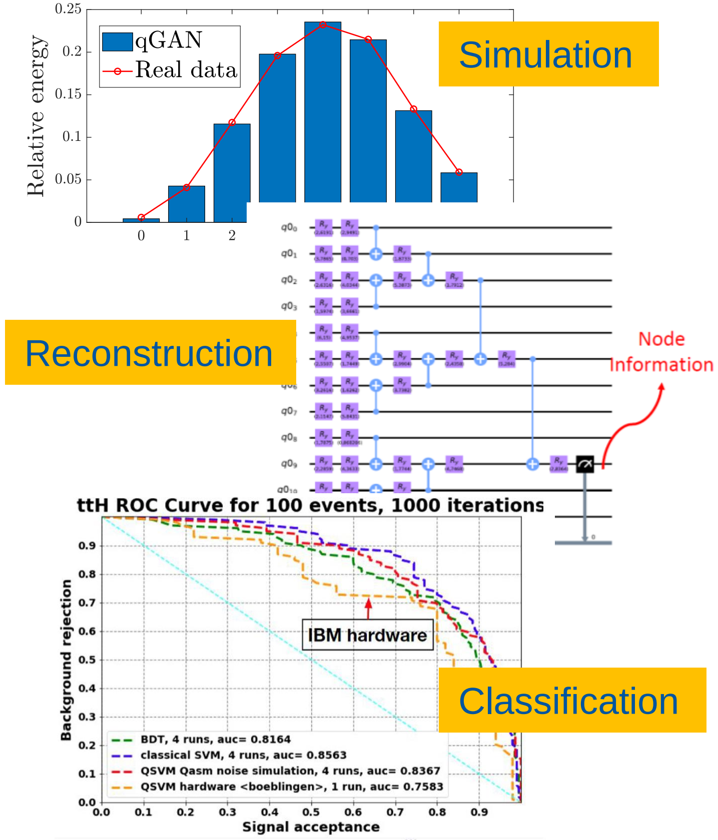
Academia, Research Labs and Agencies

Fermilab

Oak Ridge National Laboratory

Technical Programme

Quantum Computing



Today: set a baseline for prioritisation and systematisation

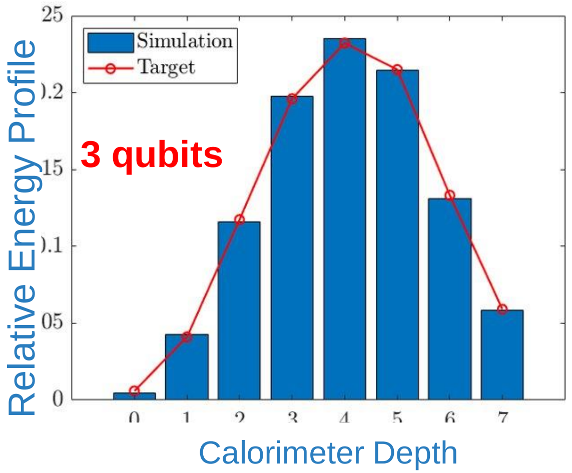
- Quantum **Generative Adversarial Networks** for detector simulation
- Quantum **Graph Neural Networks** for particle trajectory reconstruction
- Quantum **Support Vector Machines** for signal/background classification (Higgs, SUSY,..)
- Workload optimization via quantum **Reinforcement Learning**
- Quantum **Random Number Generators** tests and integration
- Quantum **Homomorphic Encryption**

Later: focus on a more formal approach to algorithms, methods, error characterisation and correction

Hybrid Classical-Quantum GAN

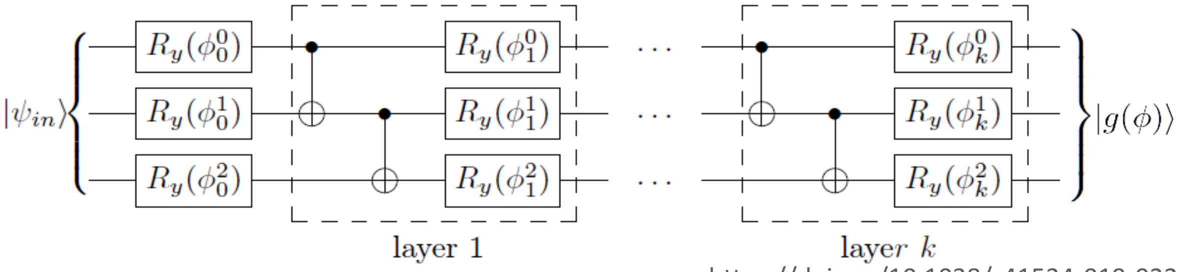
Sofia Vallecorsa, CERN

IBM qGAN can load probability distributions in quantum states

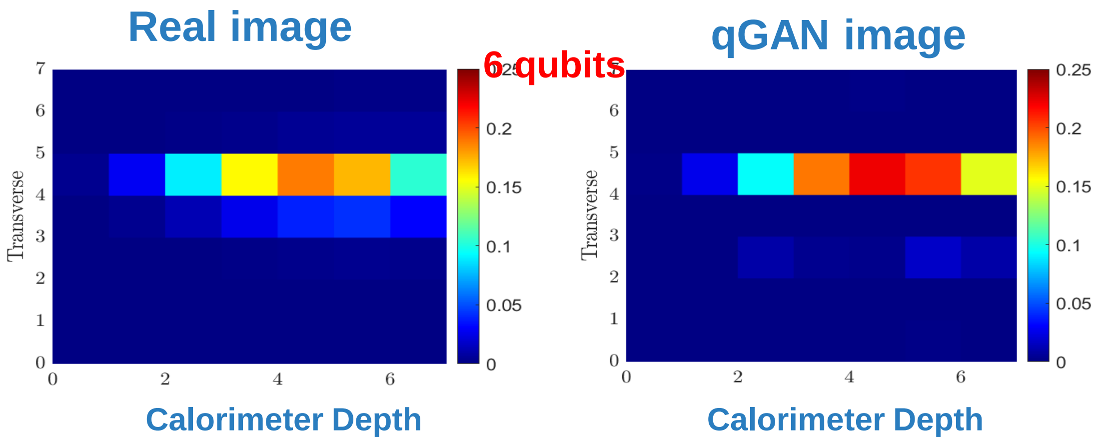


- 1D & 2D energy profiles from 3DGAN images
  - 2^n classical pixels expressed by n qubits
- Train a hybrid classical-quantum GAN to generate **average image**

Quantum Generator: 3 R_y layers



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



Need a way to **sample single images**

Extending the qGAN model

Sofia Vallecorsa, CERN

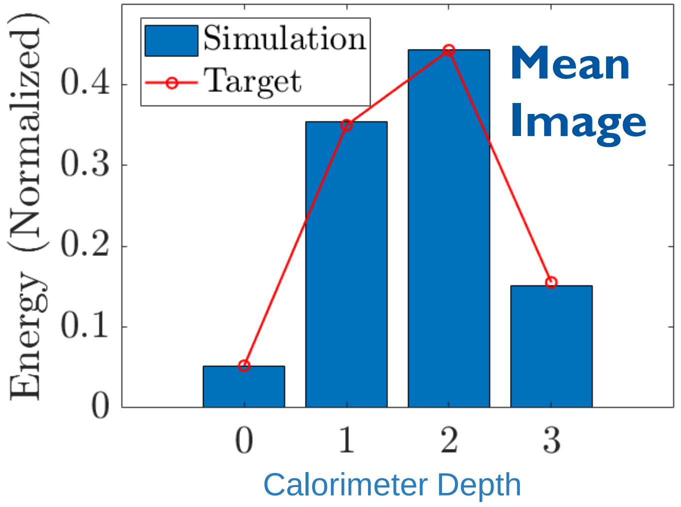
Collaboration with Cambridge Quantum Computing

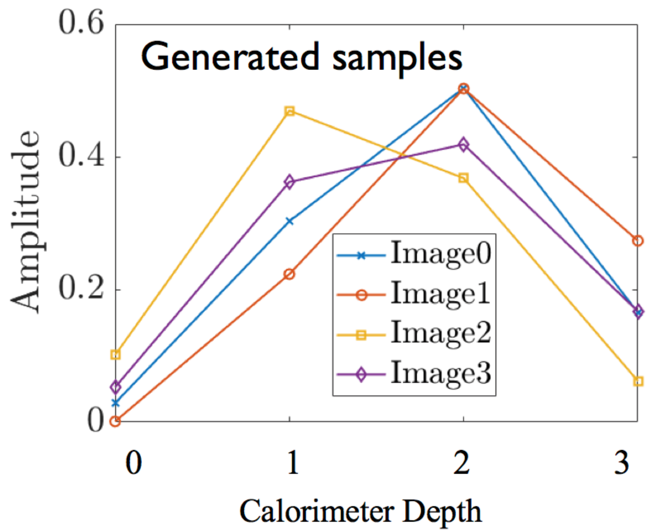
Two-steps quantum generator to learn the average distribution and sample images from it

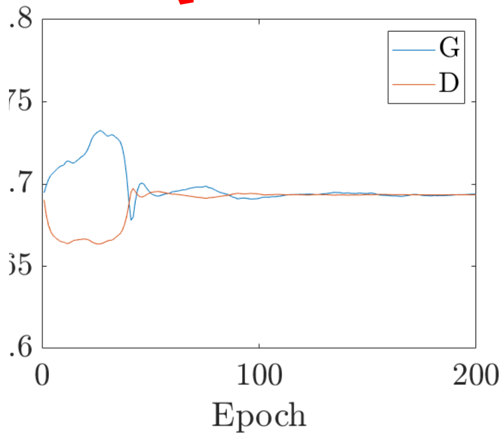
Ry variational form implemented using **qiskit & t|ket**

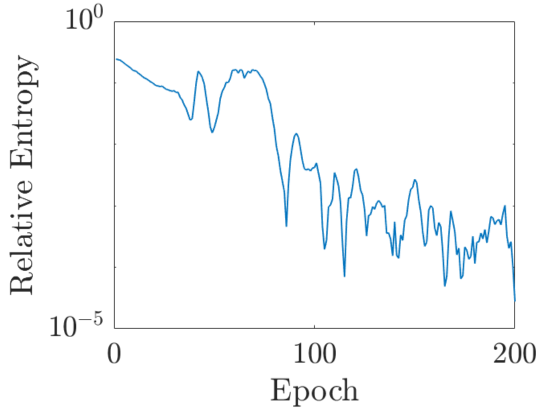
Classical discriminator (pyTorch) 4 nodes → 512 nodes → 256 nodes → 1 node

WORK IN PROGRESS









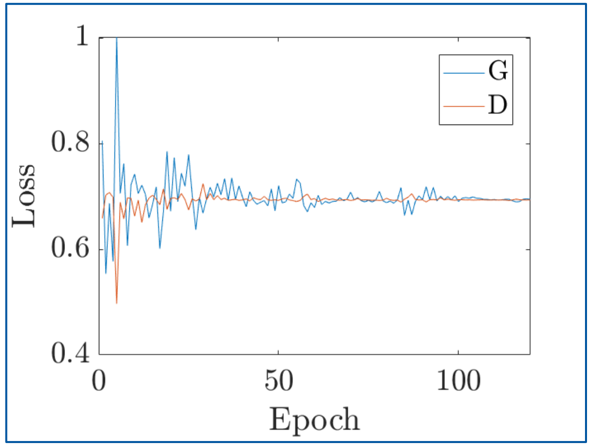
Su Yeon Chang: ML4PS @NeurIPS20
Sofia Vallecorsa, CERN

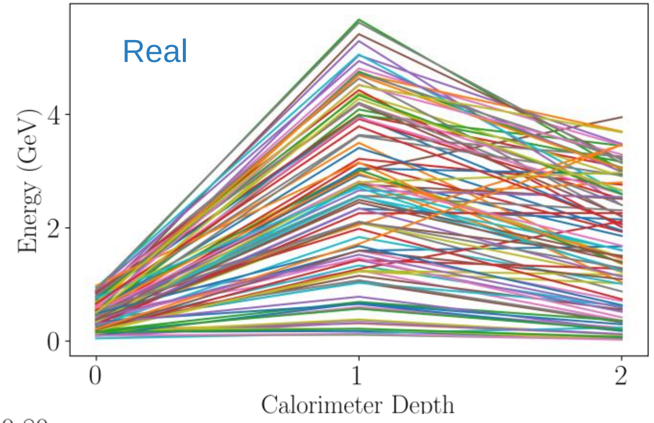
Continuous Variable qGAN

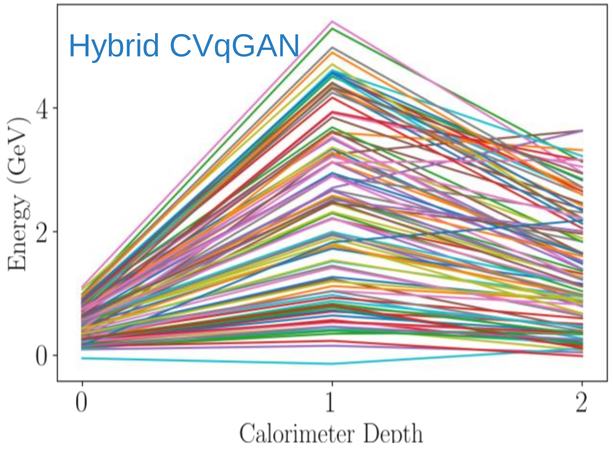
Alternative concept based on optical systems

Information encoded in continuous physical observables

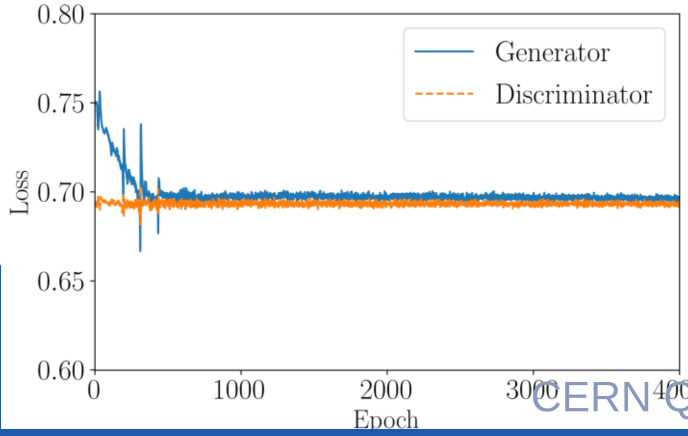
Hybrid model: 8 layers quantum generator (**264 parameters**)
Fully connected classical discriminator (44k parameters)
Converges in ~**100 epochs**

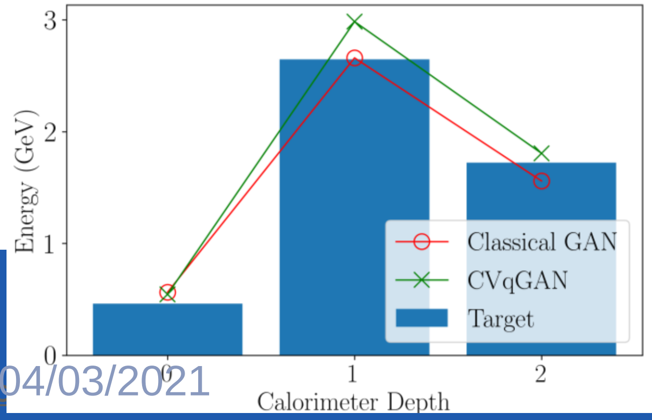






Classical GAN:
Fully connected generator (**44k parameters**)
Converges in ~**1000 epochs**

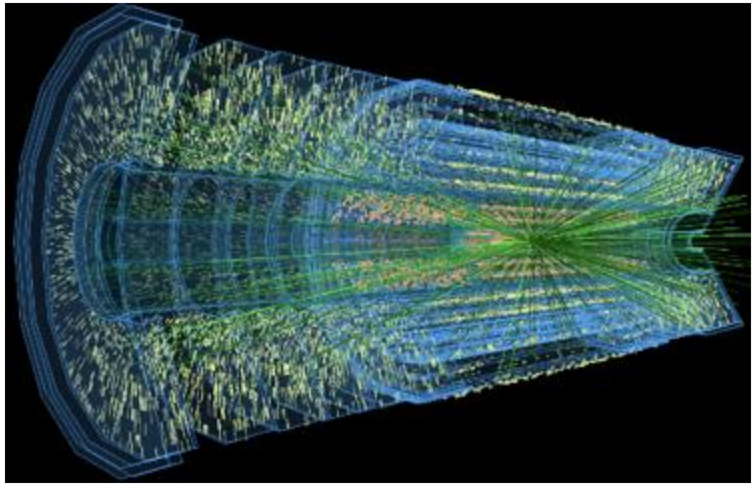




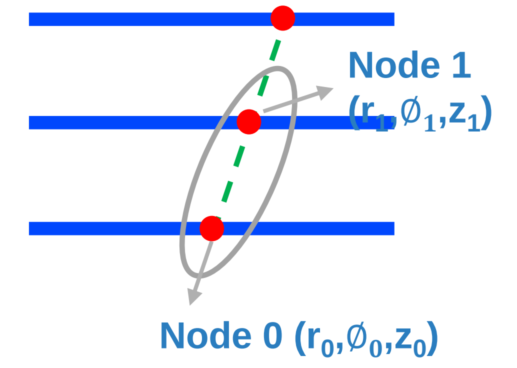
Sofia Vallecorsa, CERN

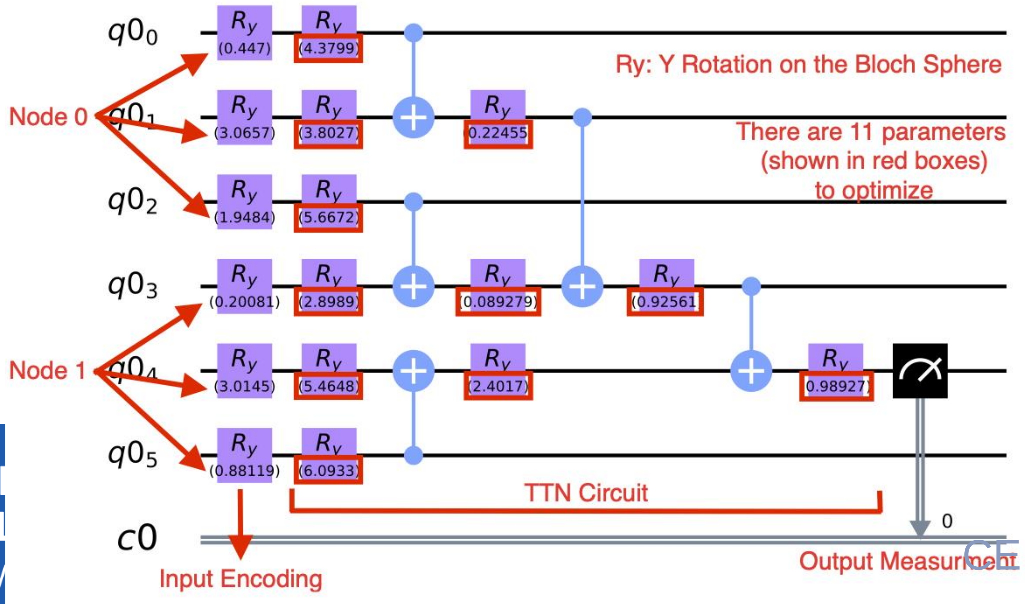
Quantum TTN for tracking

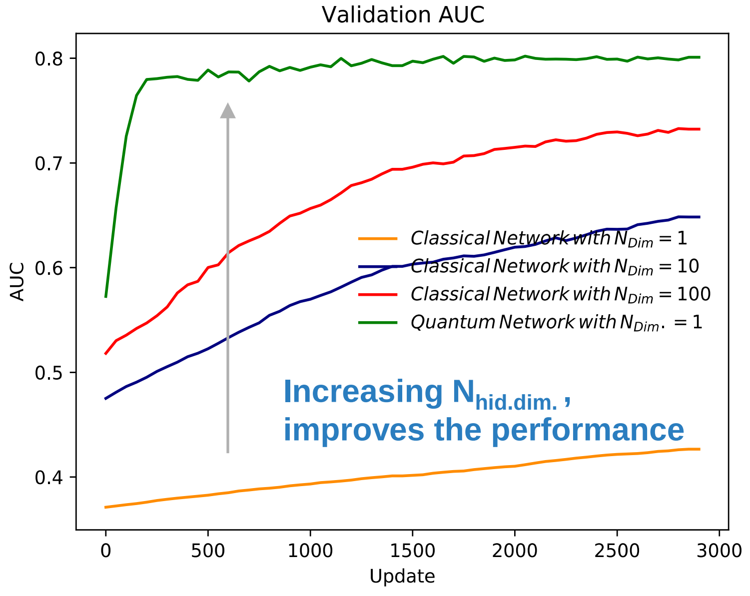
arxiv:2003.08126



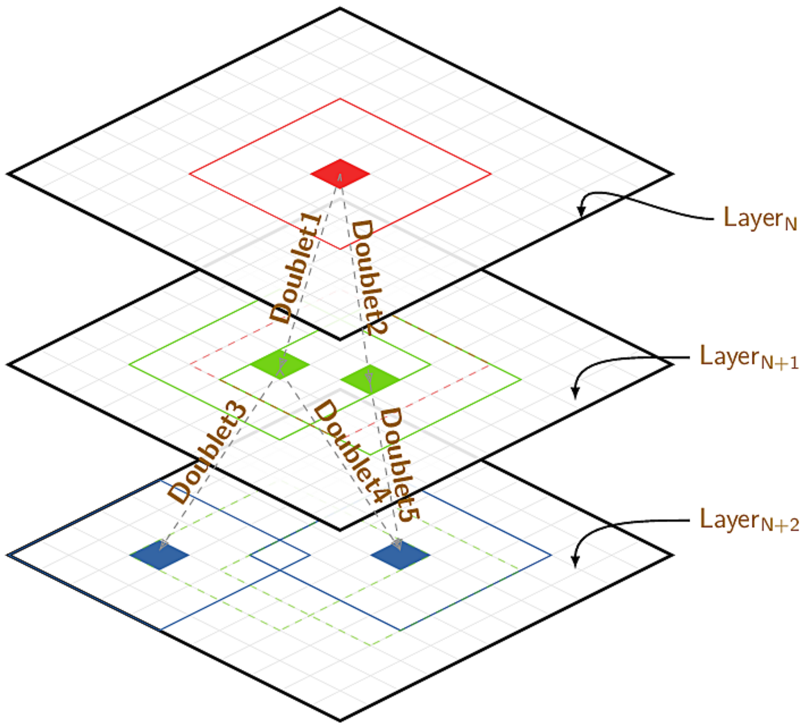
- **Q-TrKx project** designs a cascade of TTN to perform trajectory reconstruction from detector digital hits
  - Mimics classical GNN based approach (**HEPTrk**)
  - Realistic dataset used for TrackML challenge
- Comparison to simple classical networks shows **quantum potential**







CMS QTrack



https://hgcal.web.cern.ch/Reconstruction/TICL/

Investigation and development of QML algorithms for the TICL (***T**he **I**terative **CL**ustering*) Framework as part of the CMS HGCAL development.

TICL uses pattern recognition and linking algorithms to create 3-d objects or showers (*tracksters*) from, 2-D cluster layers.

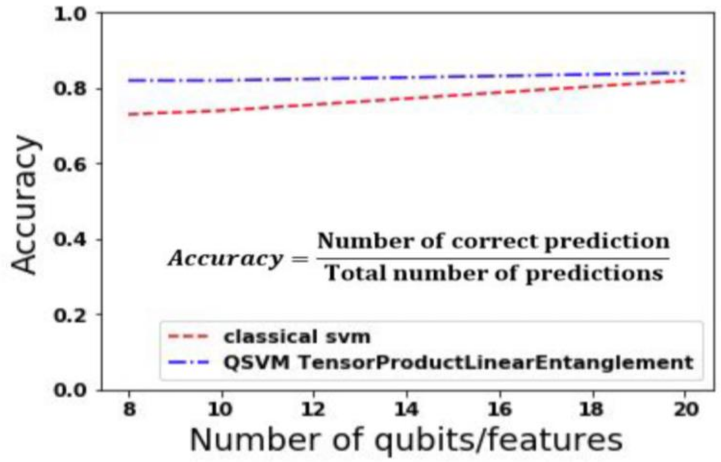
The goal of the QTrack project is to develop new quantum pattern recognition and linking algorithms for TICL and the underlying, highy-parallelisable CLUE (***CLU**stering of **E**nergy*) algorithm.

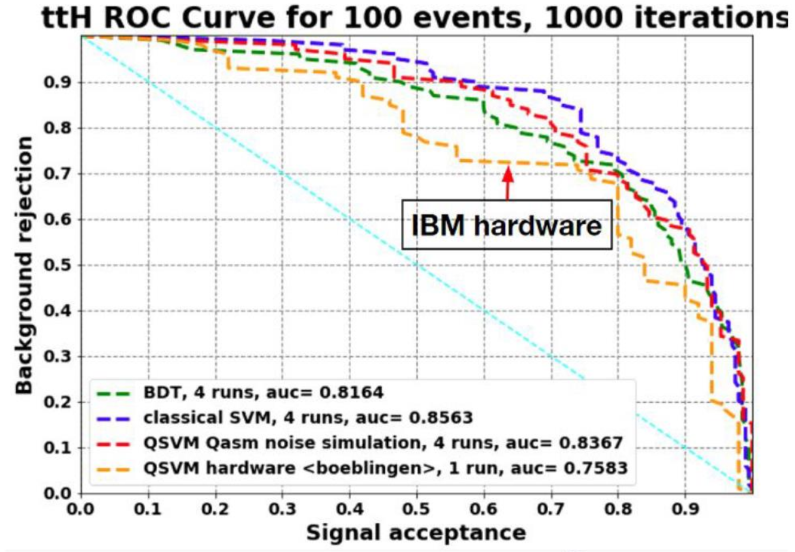
Quantum SVM

Chan et al PoS, LeptonPhoton2019 49 (2019)
Prof. Saun Lan Wu and her team

A quantum classifier for Higgs boson identification: ttH(H $\rightarrow \gamma\gamma$)

- 45 signal/background classical distinctive features
  - Reduce number using PCA (5 qubits)
- Implement a Support Vector Machine **as Variational circuit in Qiskit**
- Comparison to classical BDT and SVM
  - 1000 iteration on IBM boeblingen
- Quantum simulation requires **large computing resources**
  - **Memory increases** with qubit, training events and complexity





ttH(H->$\gamma\gamma$) AUC	AUC
Classical SVM	0.856
XGBoost BDT	0.816
QSVM Simulation with Noise	0.837
QSVM Hardware	0.758

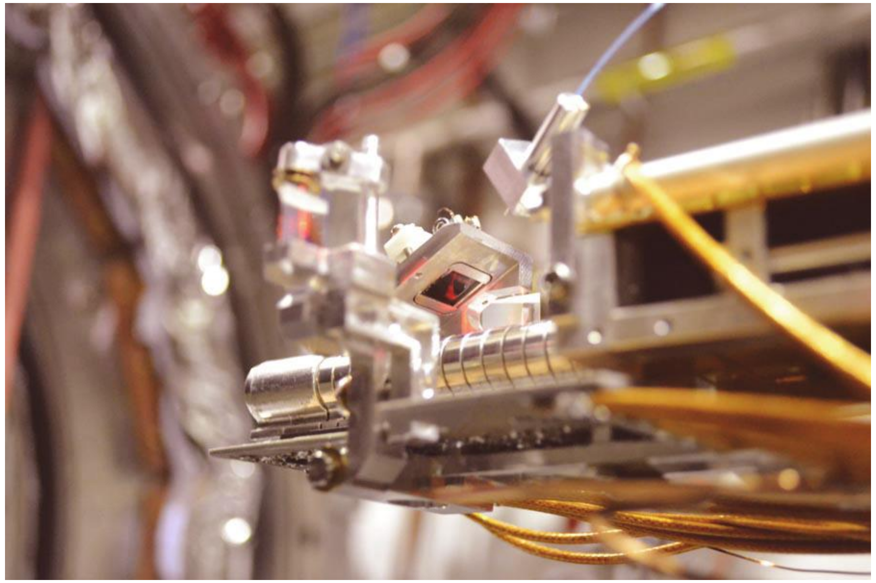
QC Simulation Platform

1 Enable building skills and starting R&D work, both as a preparation to real H/W and to explore “quantum-inspired” computational models

2 “Standardized” access to different simulators, hardware, tools, libraries (e.g. pre-packaged containers, Jupyter notebooks, GitHub, etc.)

3 Multiple participating sites, capitalizing on CERN world-level expertise in operating distributed infrastructures

Quantum Sensing and Low-Energy Physics



Scope

Low-Energy Physics: antimatter, dark matter searches, symmetries, EDM's (AD, AeGIS,
ISOLDE, etc.)

Strategy

Discrete processes, changes of quantum states

Applications

Novel devices: nanowires, photon upconverters, microwaves, magnetic junctions, SQUIDs, TES

Measurements of properties of trapped, atoms, ions, molecules, Rydberg atoms, neutral systems

Correlations of entangled systems: e.g. $e^+ e^-$ 3γ decay: simultaneous measurement of E, polarization and direction

Michael Doser, CERN

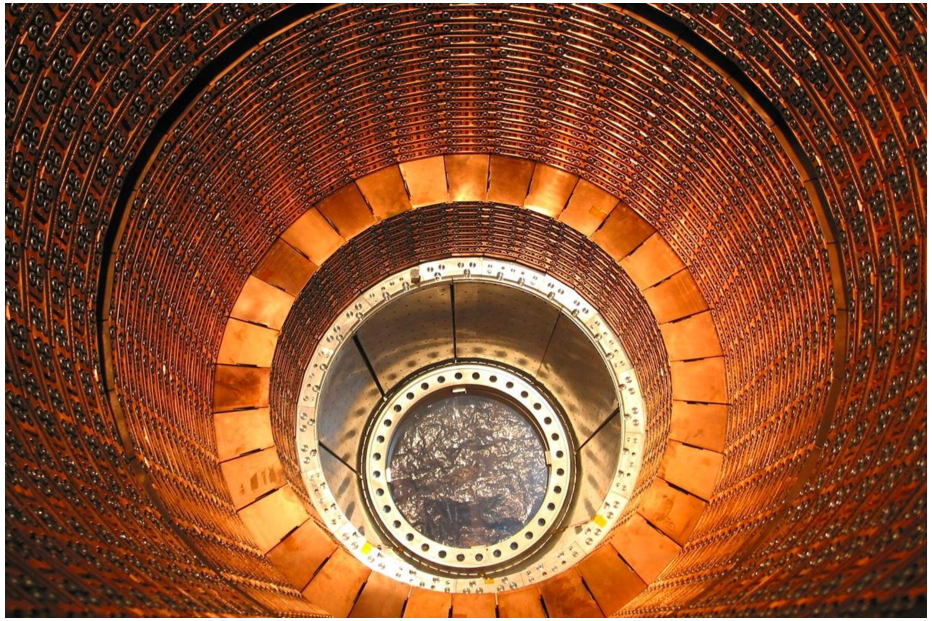
Quantum Sensing for High-Energy Physics

Scope

High-Energy Physics, particle tracking, calorimetry, identification in HEP detectors

Strategy

Quantum “priming” of detectors before measurement, signal enhancement
by laser excitation, quantum effects due to size, cryogenics



Applications

Chromatic particle trackers composed of arrays of nanodots of varying size, nanocrystals (eg. XPbBr3) as scintillator or charged particle tracking for HEP detectors
Calorimeters and low-energy single-particle (photons, mip’s, ions,...) detectors made of arrays of nanowires (SNSPD)
2D-structures (graphene) for gaseous detector signal amplification, synergies with atomic and quantum optics experiment control/DAQ

Quantum Infrastructures

CERN started the Web; we have some expertise it's in our DNA ☺

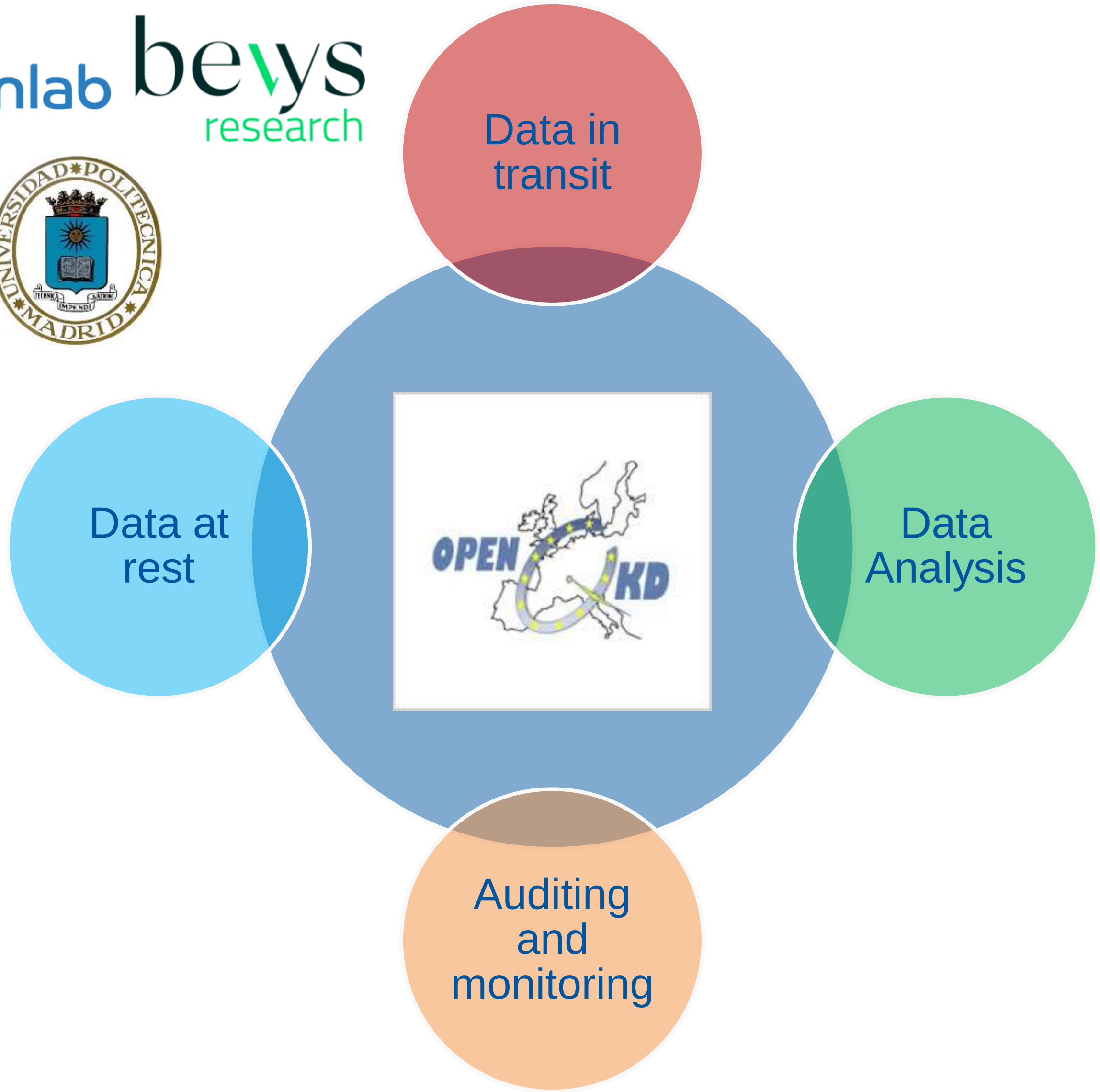
CERN was part of early quantum networks experiments already 10+ years ago

Interest in taking part in EU and international network deployment initiatives to build the future ***Quantum Infrastructures***

Quantum memory/storage would be necessary for our typical "big data" models

QUANTUMACY

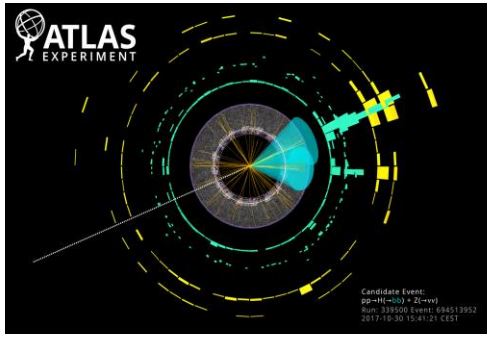
- **QUANTUM-based privacy and self-determination**
- Funded as an openQKD open call project
- End-to-end use of **QKD** to secure distributed data analysis over cloud infrastructures
- Data analysis: **quantum homomorphic encryption, SMPC**
- Auditing: **quantum block chains**
- **Medical use cases**: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



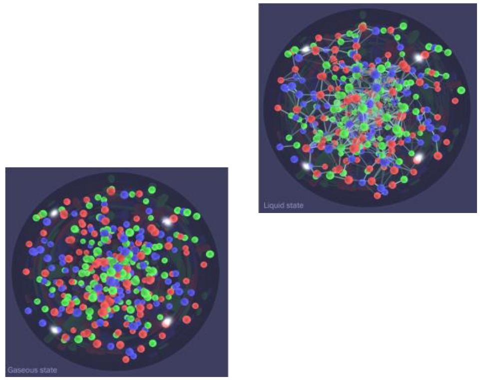
QUANTUM TECHNOLOGY INITIATIVE

Quantum Physics and Information Theory

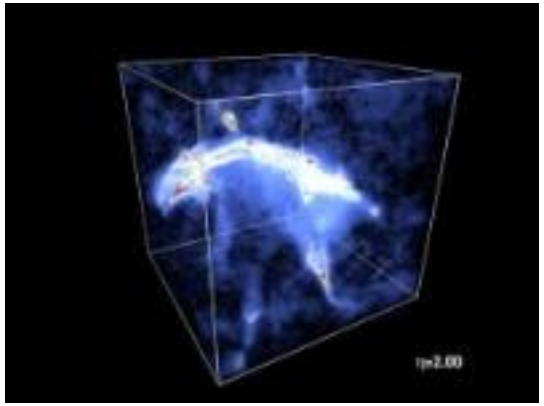
Modern-day particle physics demands large-scale computing



High-Energy Collisions
Monte Carlo simulation of hard, soft and hadronizing processes

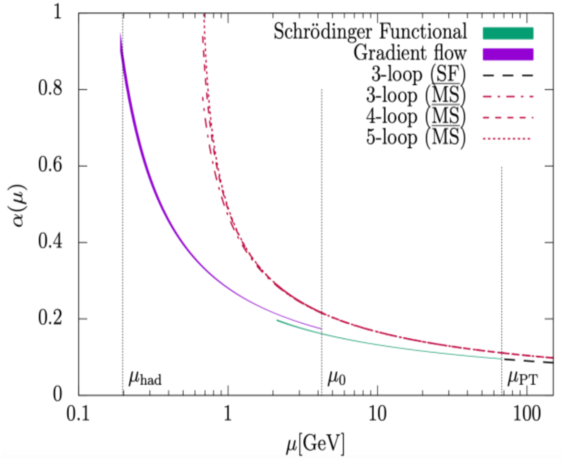


Heavy-Ion Physics
Hydrodynamic evolution of quark gluon plasma



Cosmology/AstroParticle
Evolution of axion field in early universe (https://www.youtube.com/watch?v=1By1DMq1EpI)

arxiv: 1906.00967



Lattice QCD
Monte Carlo evaluation of Euclidean correlation functions

ALPHA collaboration
arxiv: 1706.03821

Dorota M. Grabowska, CERN

Areas of investigation

QCD Applications

Simulations for collider physics

QCD phase diagram

Hadronic physics

Multi-loop amplitude calculations

Heavy Ion Simulation

High multiplicity collisions

Non-equilibrium phenomena

Quark-Gluon Plasma

BSM + Cosmo Applications

Early Universe simulations

Neutrino Oscillations

Feasibility investigations

Can we address problems not reachable with classic computing?

Classical Simulation

Software development for quantum simulators on classical hardware

Replacing Existing Codes

Investigating hybrid classical-quantum algorithms

Quantum Information

Error correction and mitigation

Speed-up investigations

Can we speed up solutions compared to classic computing?

Education and Training

Education Programme

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

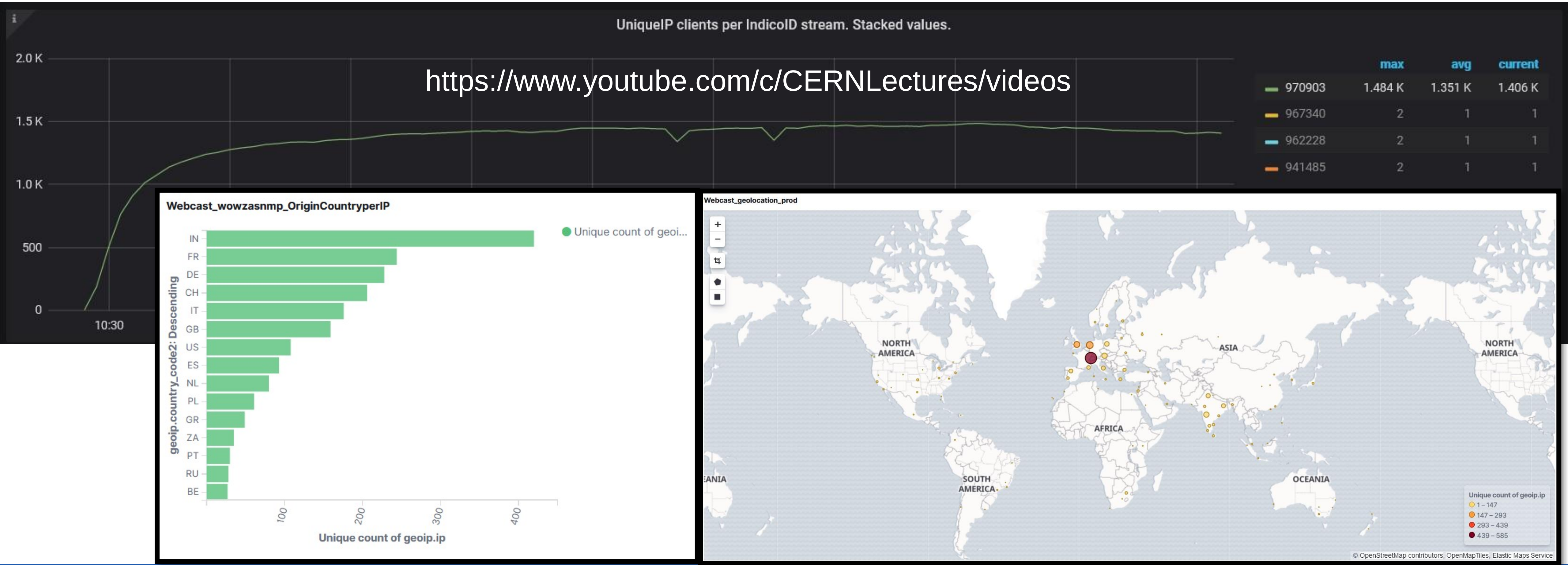
- Lectures and seminars with field experts (in collaboration with the CERN Academic Training Services)
- Training courses (in collaboration with academic and industry experts)
- Colloquia and specialistic seminars
- Hackathons
- Summer Students Programmes

QUANTUM TECHNOLOGY INITIATIVE

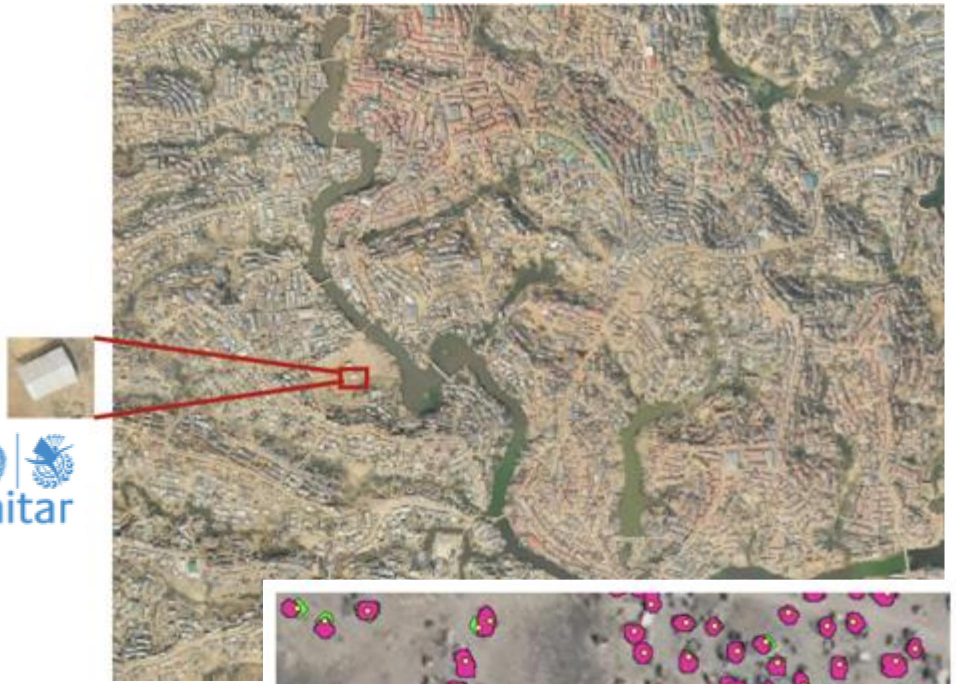
“A Practical Introduction to Quantum Computing”

A 7-part lecture series by Prof. Elias Combarro, University of Oviedo, CERN Scientific Associate (06/11-18/12/2020)

https://www.youtube.com/c/CERNLectures/videos



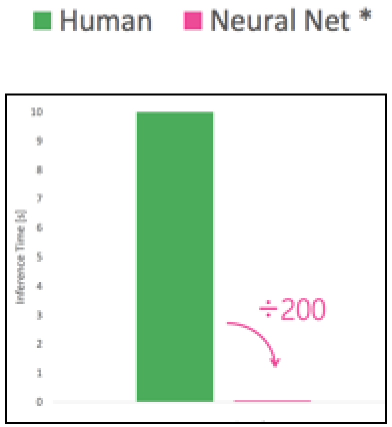
AI for Earth Observation

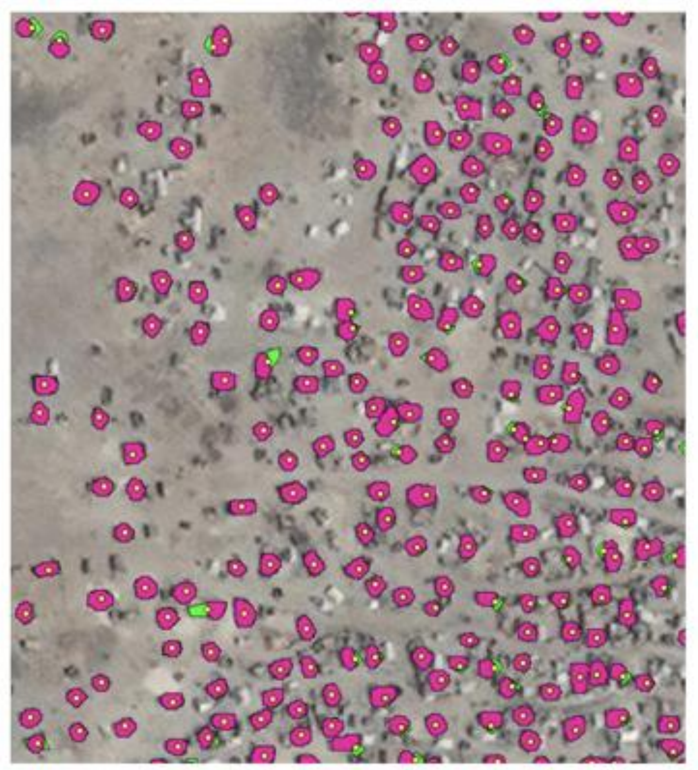


Automatic scan of high-resolution satellite images for **disaster relief**

High precision is required

Detectron Framework (FacebookAI) Unosat Adapted model





Transfer learning from Region-based CNN

Average precision is 82%, 200x speedup

ESA Twin-Earth & QC4EO

QC4EO

Collaboration among CERN openlab, ESA Φ-lab, ECMWF, DLR, TUM BGDM, and LRZ

Investigation of impact of quantum computing and quantum machine learning at the intersection between Earth Observation and High-Energy Physics (image processing, data classification, error correction, etc.)

Thanks!

https://quantum.cern/

alberto.di.meglio@cern.ch

@AlbertoDiMeglio