CERN

The CERN Quantum Technology Initiative

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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,
1.1 B CHF budget

~3’200 staff, fellows, trainees, …

>13’000 associates

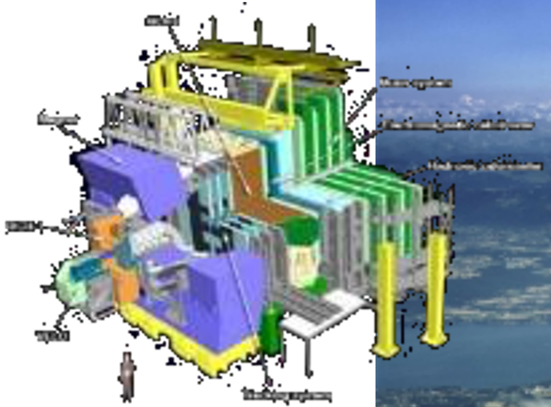
1954: 12 Member States

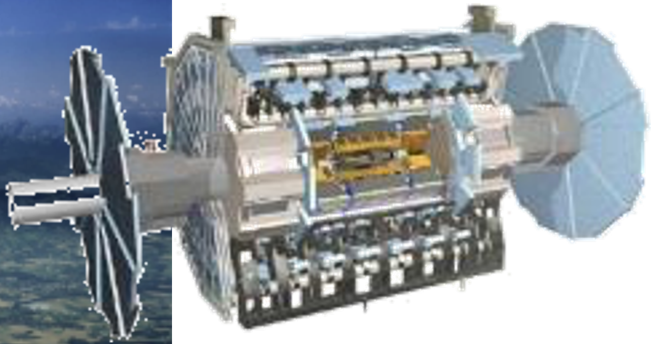
Members: Austria, Belgium, Bulgaria, Czech republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, United Kingdom
Candidate for membership: Cyprus, Slovenia
Associate members: Croatia, India,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

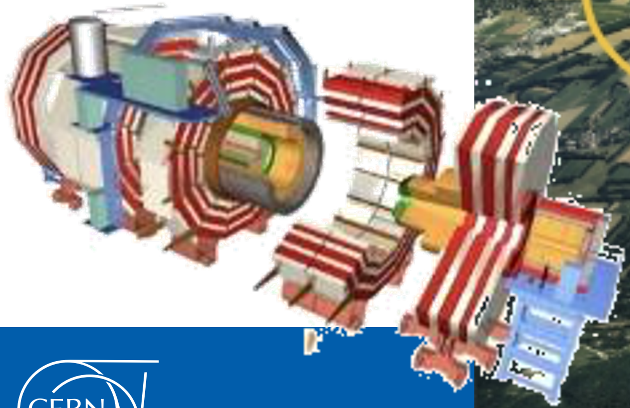
>2’500 staff members, 645 fellows, 21 trainees

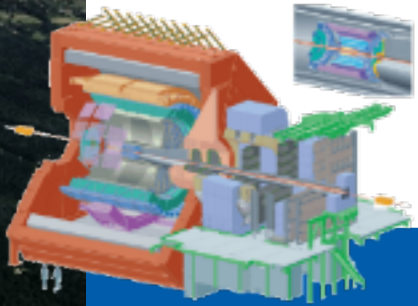
7’000 member states, 1’800 USA, 900 Russia, 270 Japan, …

The Large Hadron Collider (LHC)



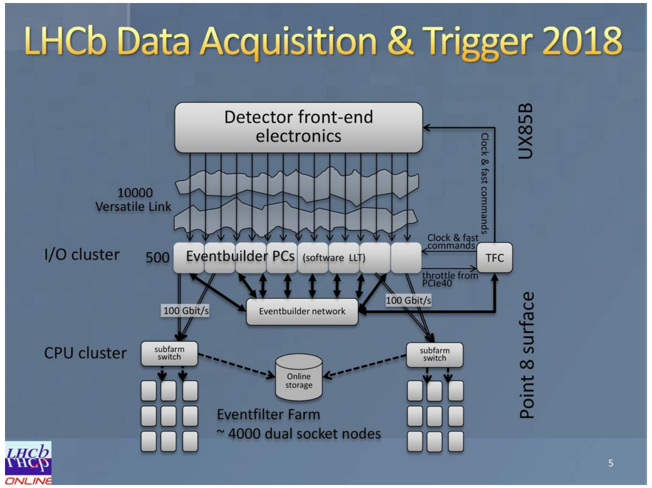






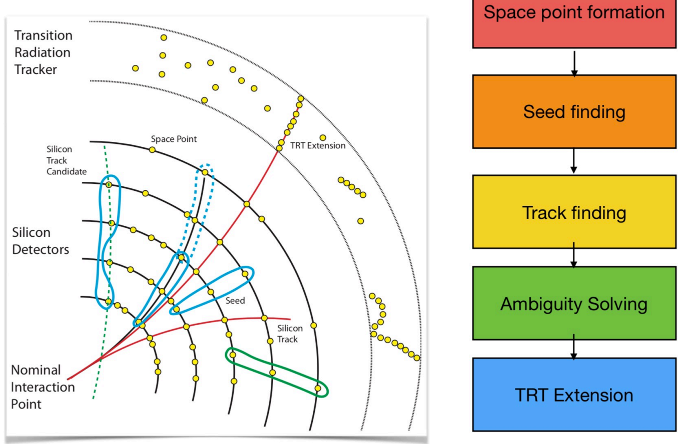
Typical LHC Experiments Workloads

© Niko Neufeld - LHCb

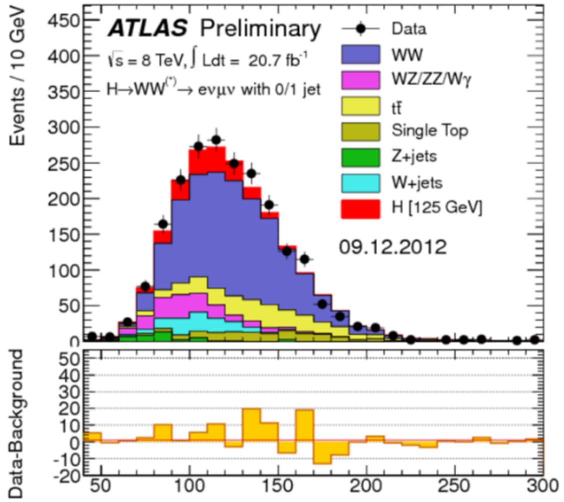


Data Acquisition

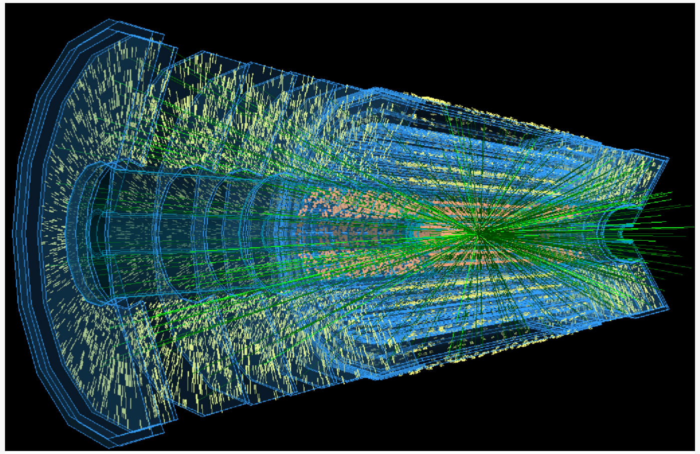
Multi-step iterative Kalman filter approach



Track Reconstruction



Data Analysis



Simulation

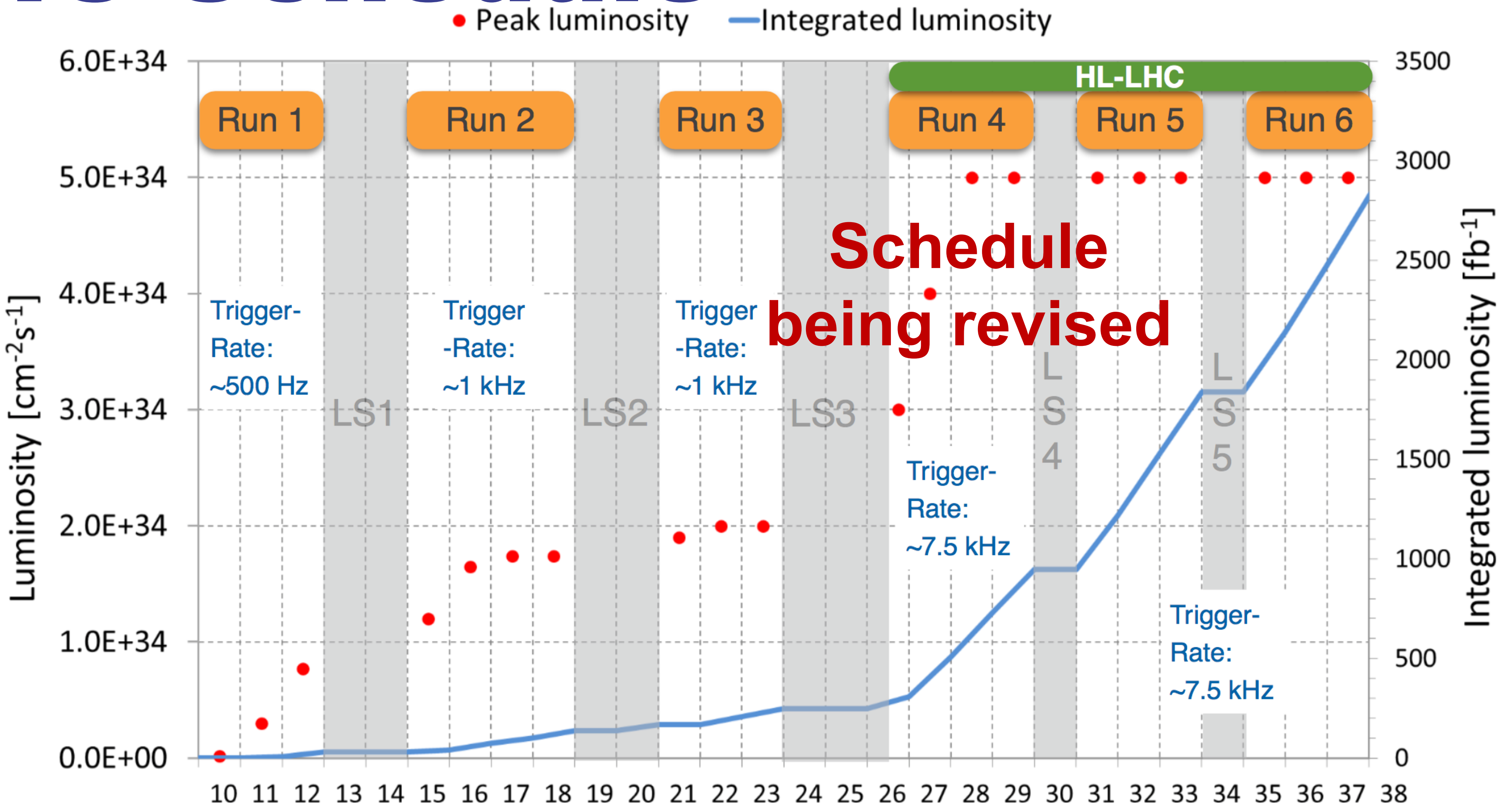
The Higgs Boson completes the Standard Model, but the Model explains only about 5% of our Universe

What is the other 95% of the Universe made of?

How does gravity really works?

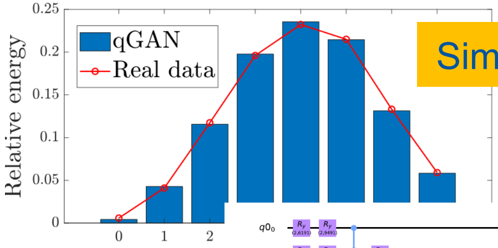
Why there is no antimatter in nature?

LHC Schedule

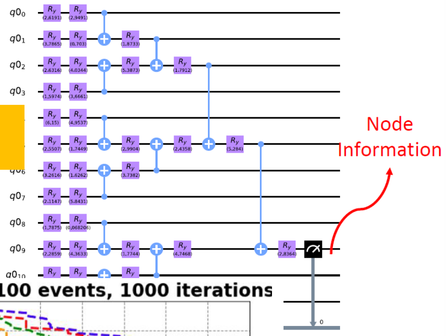


CERN Unique Expertise and Activities

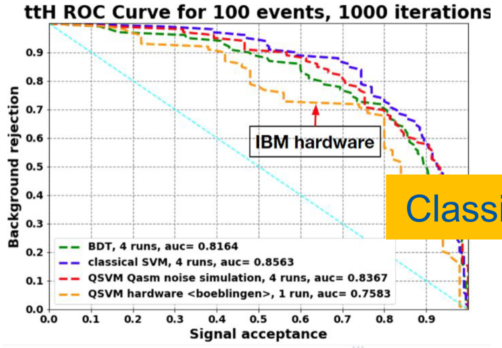
Computing



Simulation

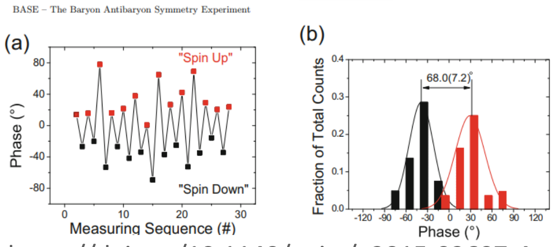


Reconstruction



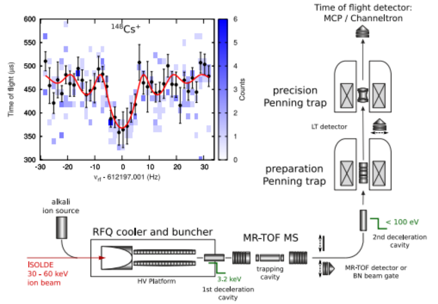
Classification

Sensing



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

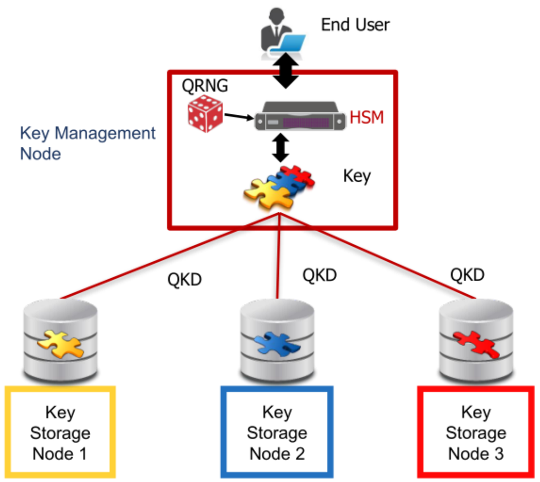
BASE phase-sensitive measurement of spin allowing very precise magnetic field drift measurements



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

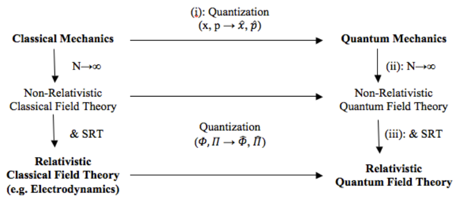
ISOLTRAP Mass-Spec

Communications

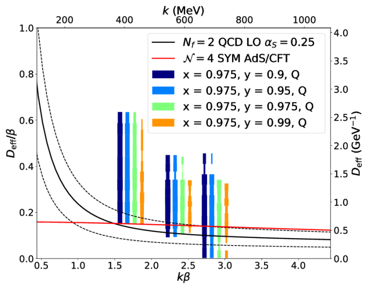


QKD node Secure Data

Theory



Quantum Field Theory



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

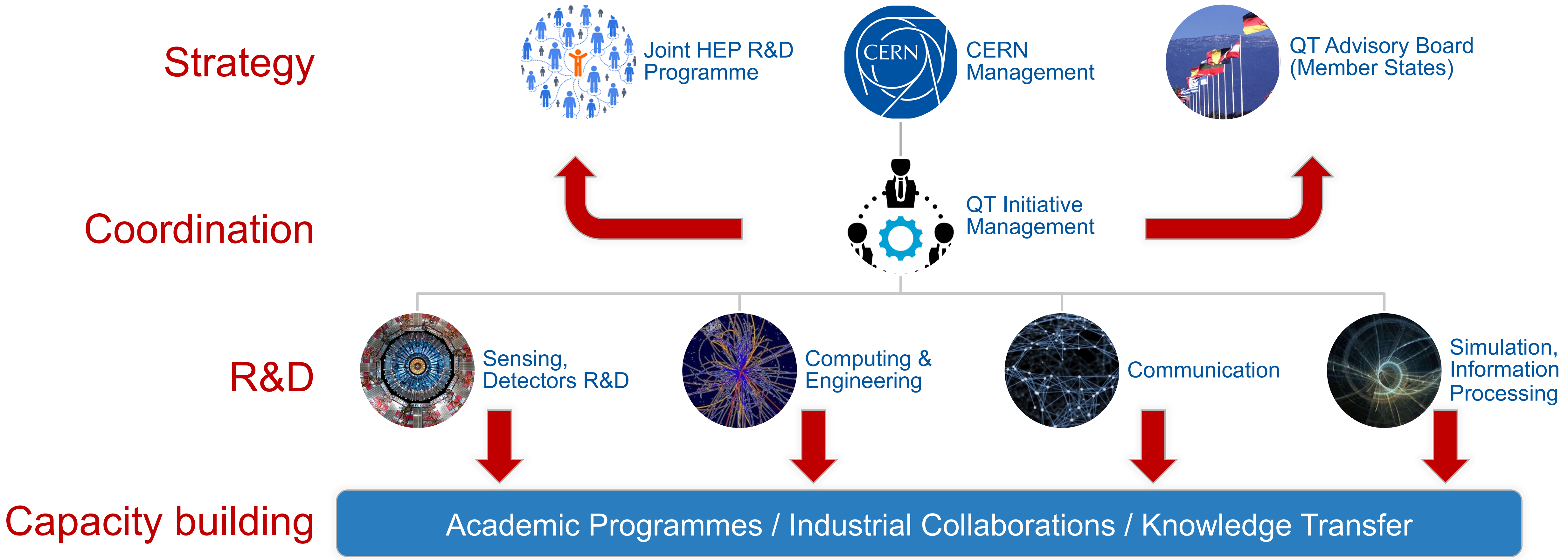
Lattice QCD

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

1st CERN Quantum HEP Workshop

- CERN openlab has organized a kick-off event of its Quantum Computing initiative on **November 5th-6th , 2018**
  - https://indico.cern.ch/event/719844/
  - > 400 registered participants from the HEP physics community, companies and worldwide research laboratories and beyond
- 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
- **CERN is now investigating ways of scaling up the QC activities in 2020**

CERN Quantum Technology Initiative



High-Level Objectives

Computing

- Assess the potential and role of QML in HEP workloads, work on optimization and more robust mathematical formulations
- Build expertise in the state-of-the-art of the software stack (simulators, compilers, programming models/languages/tools)
- Work on quantum systems simulators (FPGA?)
- Set up a distributed QCS platform

Communications

- Explore possible applications of QKD
- Comms+sensing for detectors?
- European Quantum Network/Internet

Sensing

- Ion/particle traps as computing/sensing devices
- Mass/charge/gravity sensors
- Quantum clocks
- Nanowires/nanodots for particle tracking/calorimetry
- Rydberg calorimetry

Theory

- Simulation of quantum systems
- Quantum gravity
- Information processing, error mitigation/correction strategies

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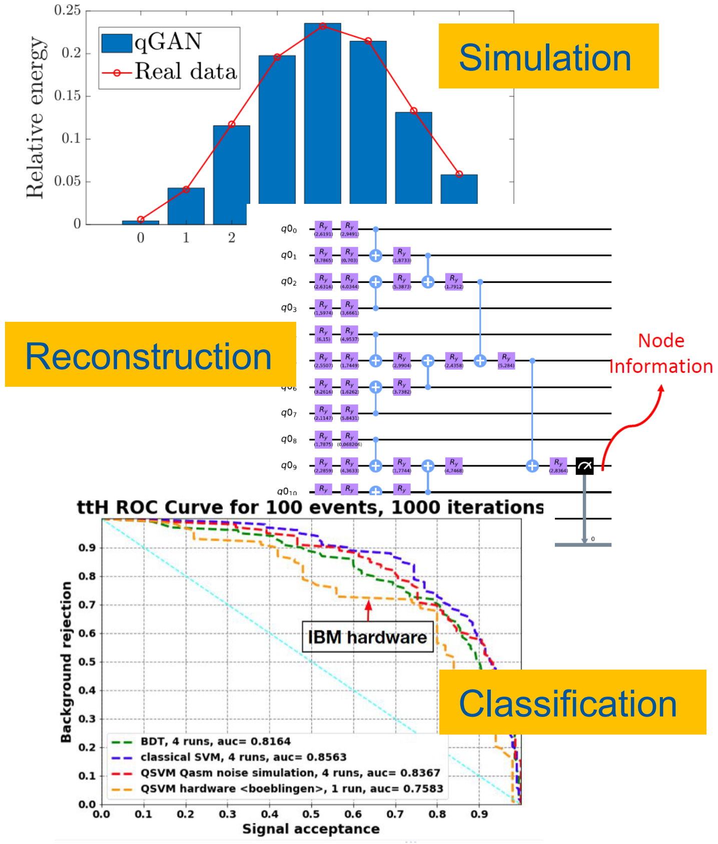
Knowledge sharing
Education
Training

Quantum Computing Projects



- 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**

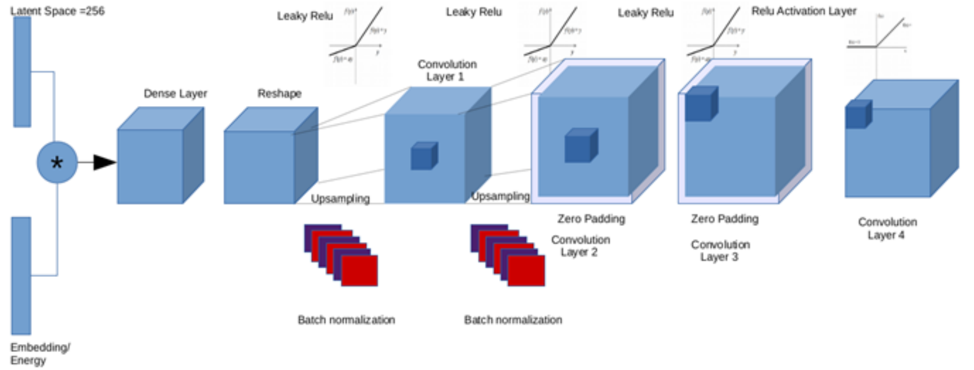
Collaborations with institutes (DESY, U. Aachen, INFN, U.Tokyo, U. Wisconsin, METU, P. U. Bucharest, U. Oviedo, …) and companies (IBM, Google, Intel, CQC, ...)

Quantum Generative Models

- Classical Generative Models can replace Monte Carlo simulation
  - **3DGAN: Generative Adversarial Networks** for calorimeter simulation
  - Detector output interpreted as a 3D image.
- Quantum Generative Models might have **larger representational power**
- **Quantum GAN** investigations**:**
  - Down sample 3DGAN use case to **manageable number of pixels**
  - **Compressed data representation** in quantum states.
    - **Qubits** or **Continuous Variables**
  - Different **hybrid** classical-quantum combinations

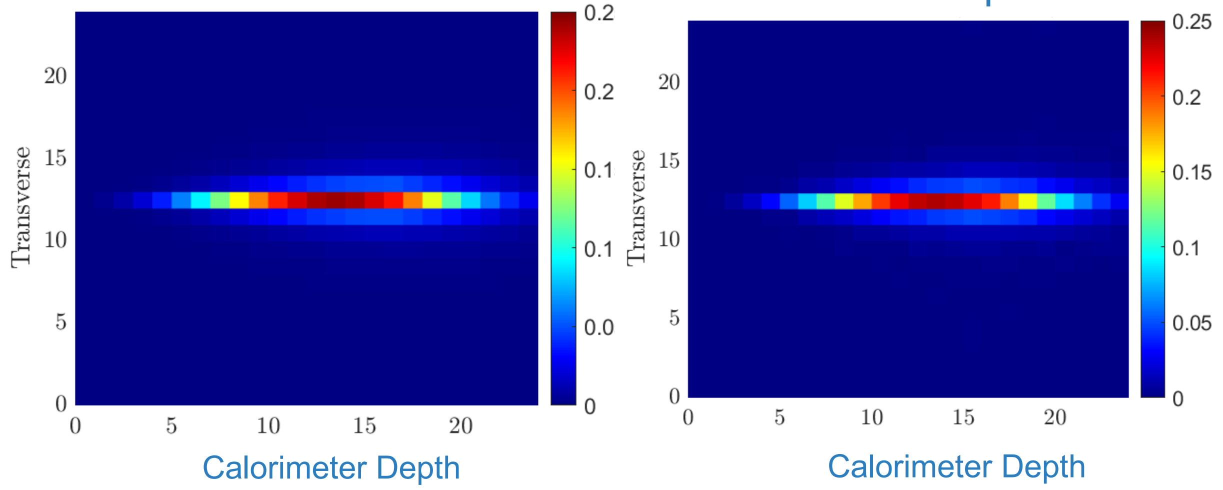
3DGAN generator

https://doi.org/10.1051/epjconf/201921402010



Real image

3DGAN output



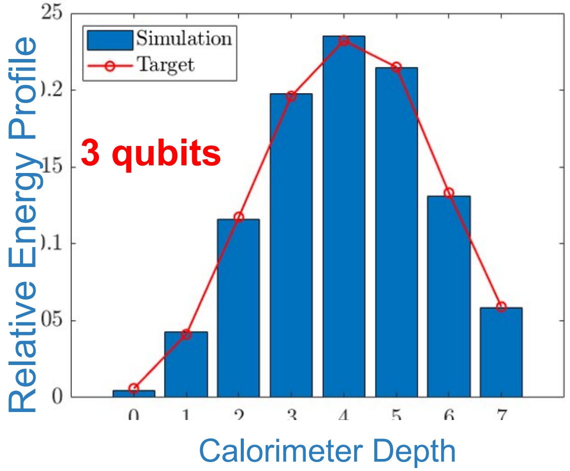
Hybrid Classical-Quantum GAN

IBM qGAN can load probability distributions in quantum states

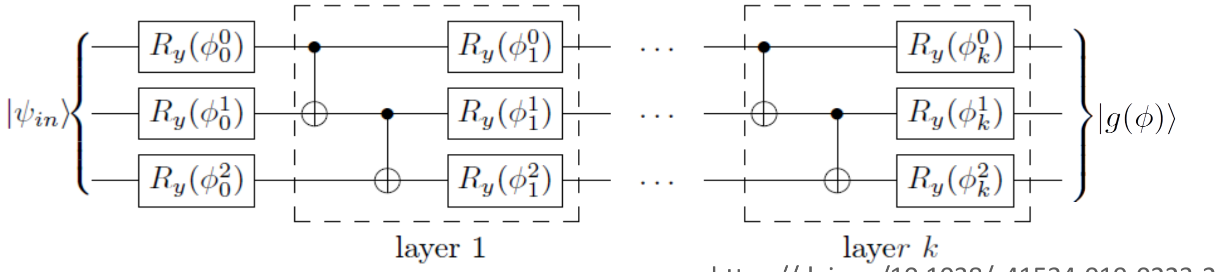
1D & 2D energy profiles from 3DGAN images

2^n classical pixels expressed by n qubits

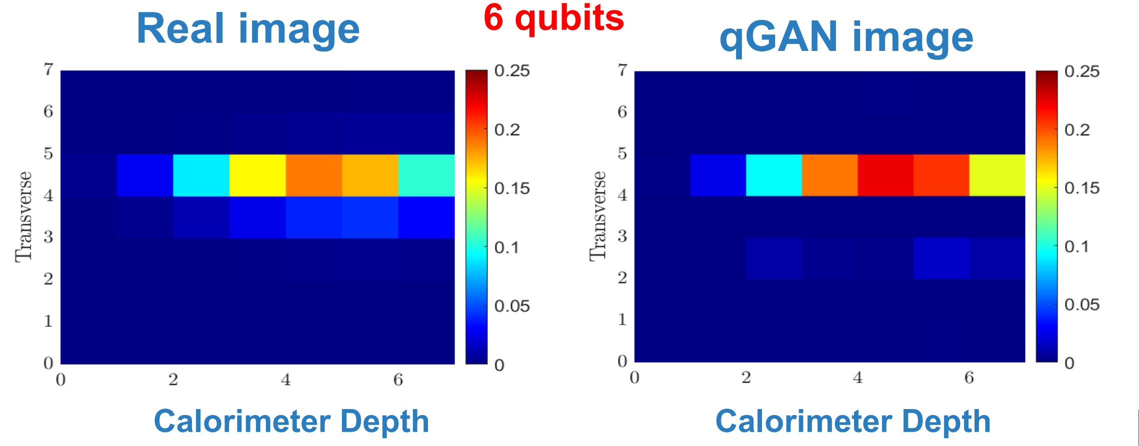
Train a hybrid classical-quantum GAN to generate **average image**



Quantum Generator: 3 R_y layers



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



Need a way to **sample single images**

Extending the qGAN model

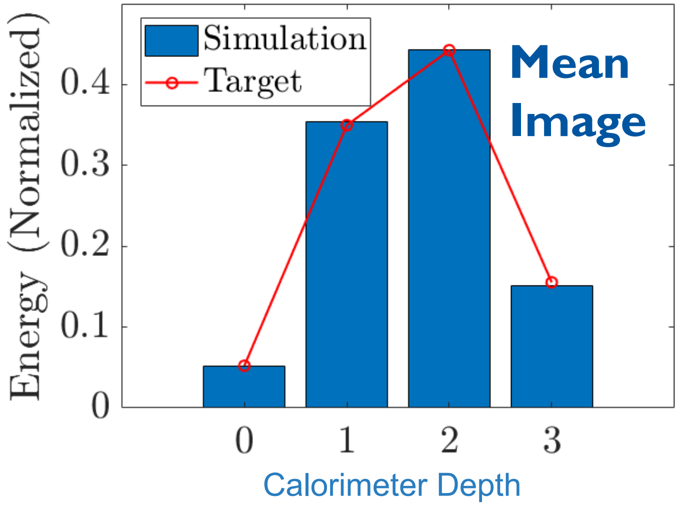
Collaboration with Cambridge Quantum Computing

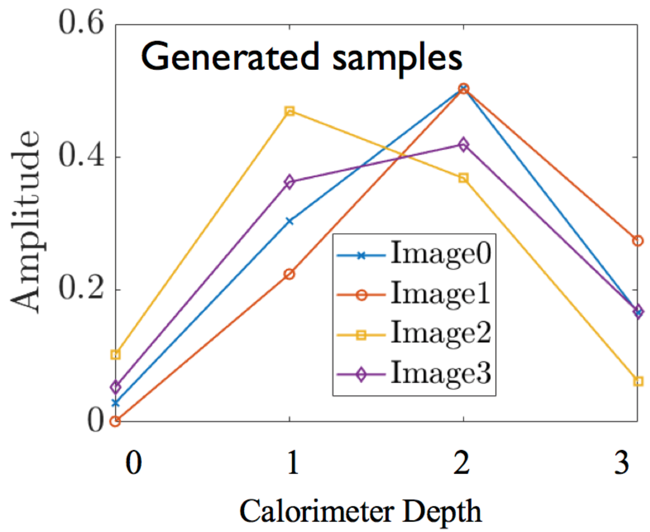
Two-steps quantum generator to learn the average distribution and sample images from it

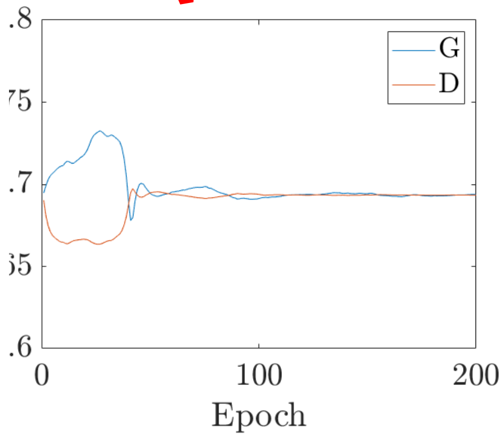
Ry variational form implemented using **qiskit & t|ket**

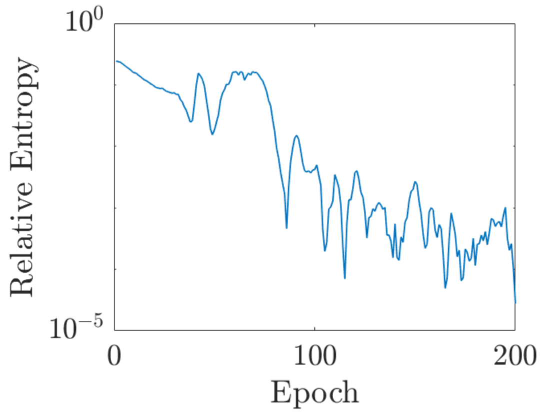
Classical discriminator (pyTorch) 4 nodes → 512 nodes → 256 nodes → 1 node

WORK IN PROGRESS





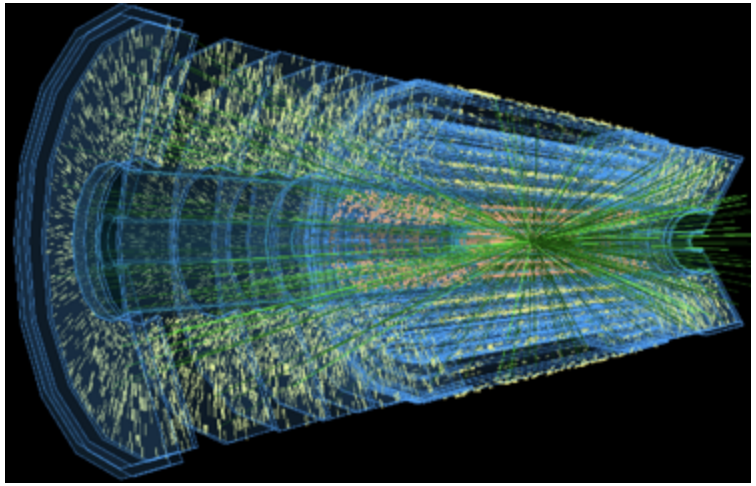


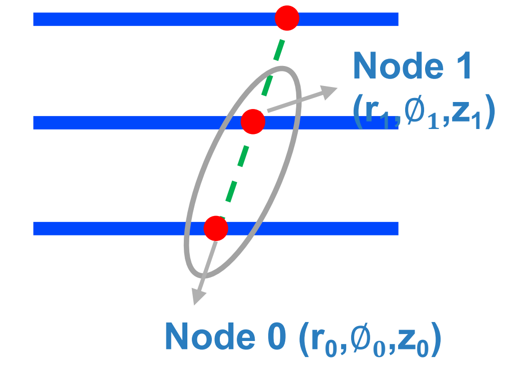


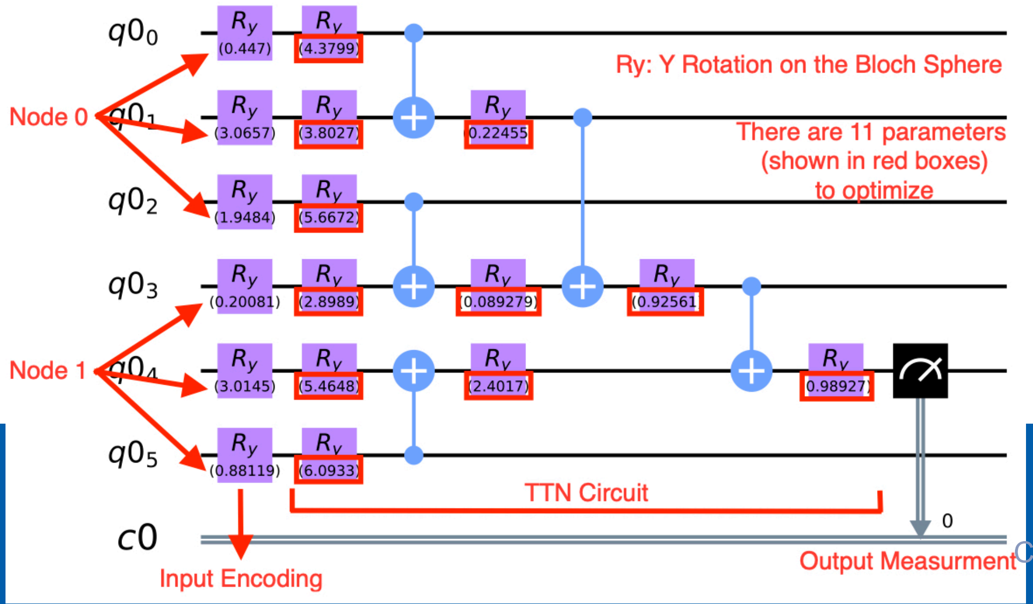
Quantum TTN for tracking

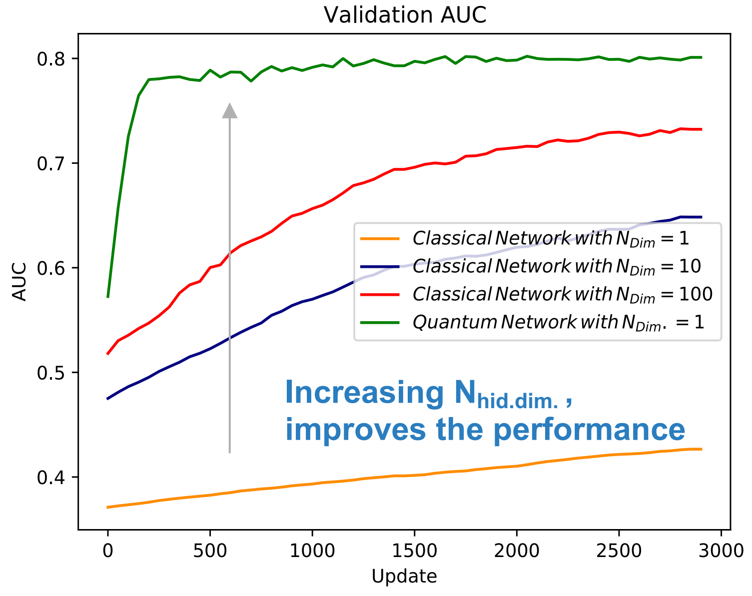
arxiv:2003.08126

- **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**







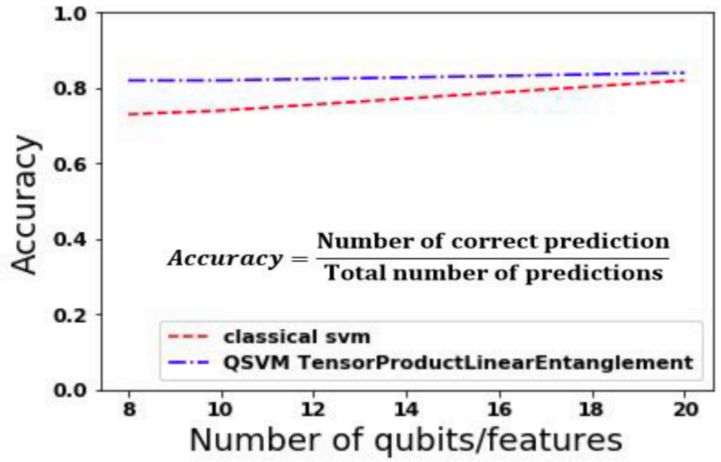


Quantum SVM

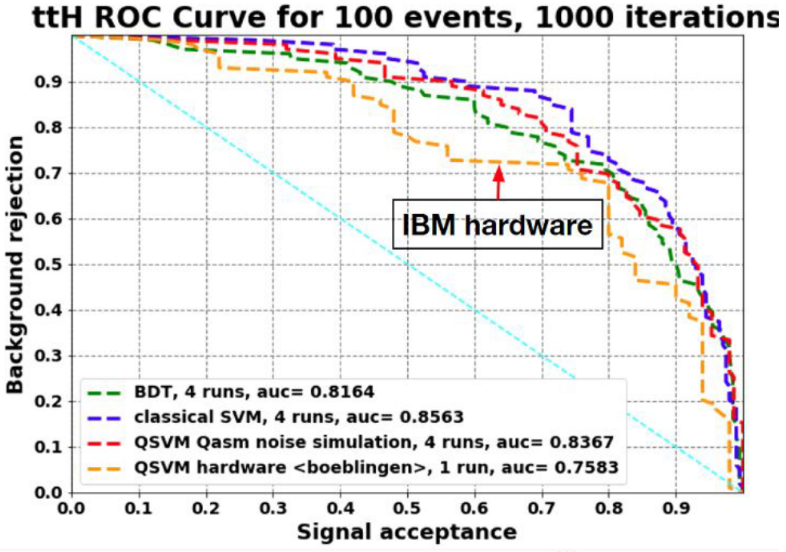
Chan et al PoS, LeptonPhoton2019 49 (2019)
Prof. Saun Lan Wu and her team

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



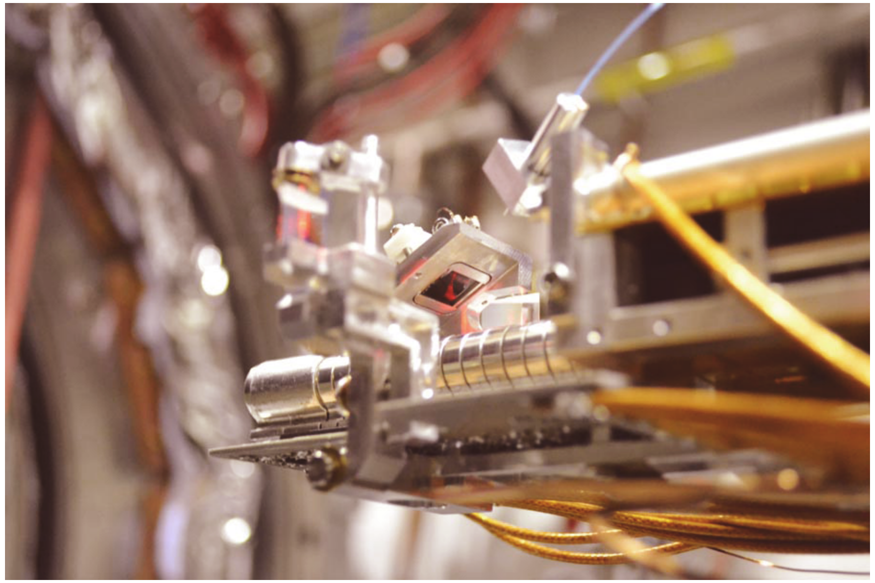
QC Simulation Platform

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

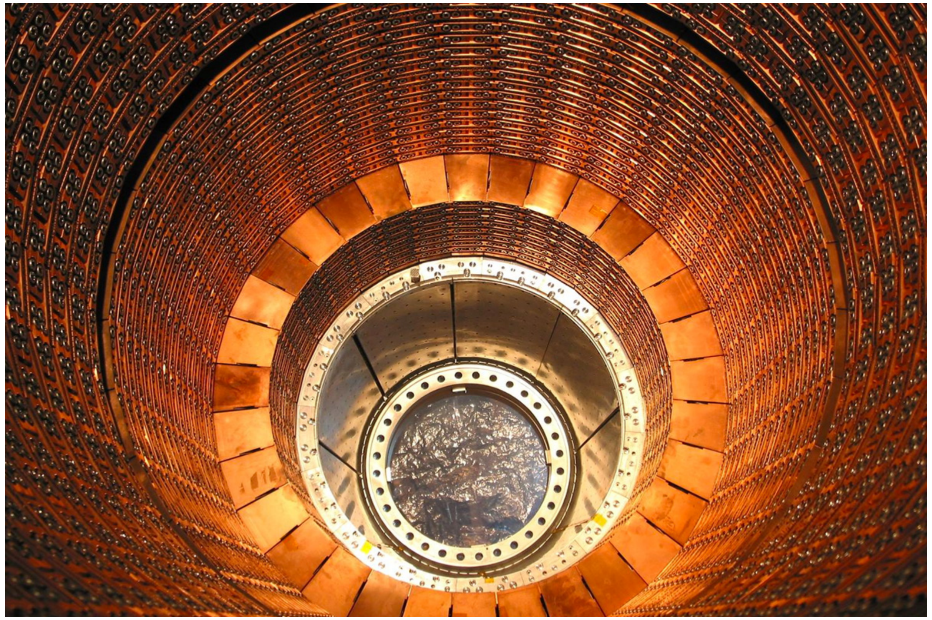
Measurements of properties of trapped, atoms, ions, molecules, Rydberg atoms, neutral systems

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

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,
Calorimeters and low-energy single-particle (photons, mip’s, ions,...) detectors made of arrays of nanowires (SNSPD)
“Rydberg-amplified” calorimeters with high dE/dx

Quantum Internet

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

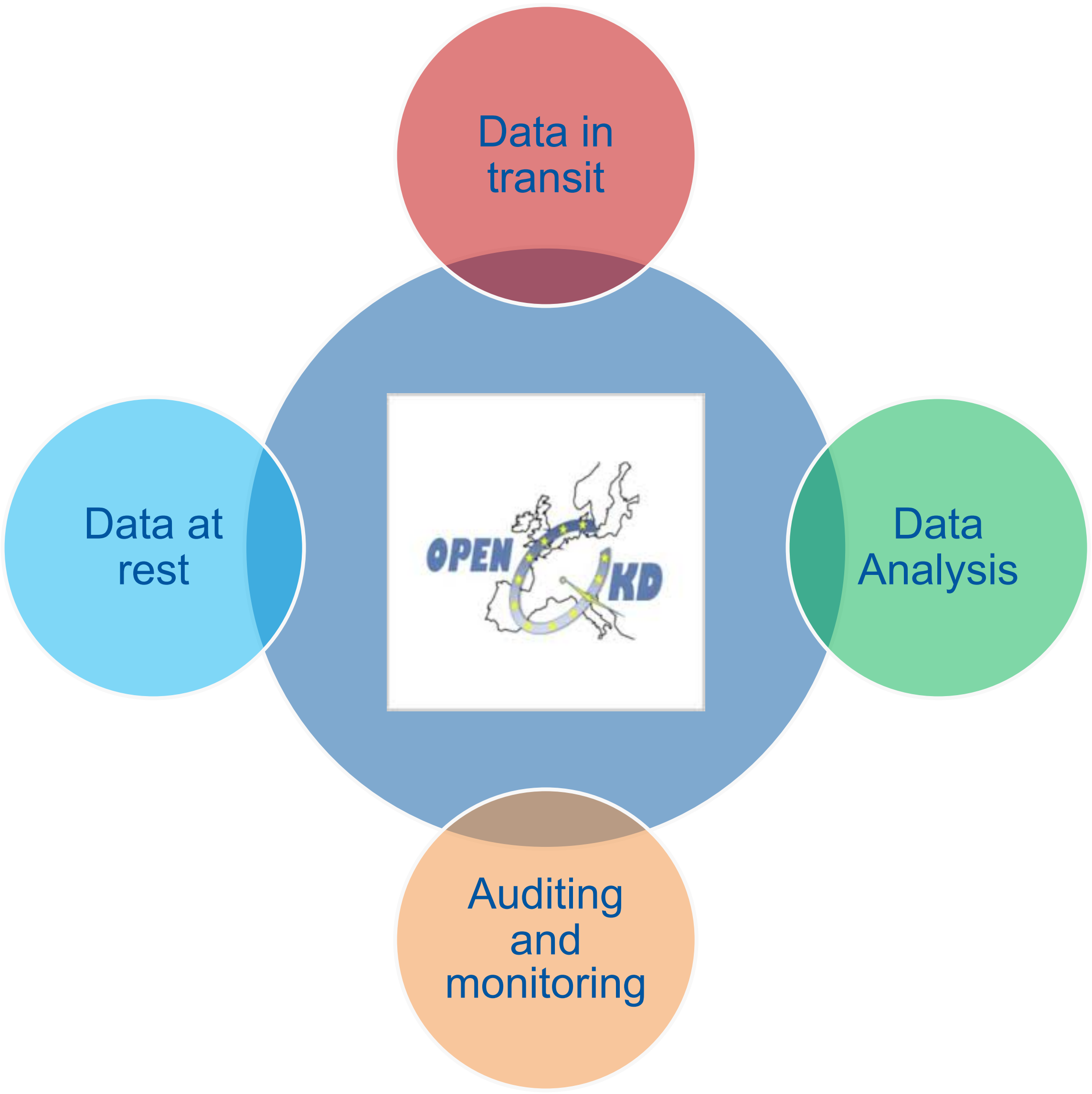
CERN was part of early quantum networks experiments already 10+ years ago

Interested in taking part in EU and international network deployment initiatives

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 funds
- End-to-end use of QKD to secure distributed data analysis over cloud infrastructures
- Data analysis: **quantum homomorphic encryption**
- Auditing: **quantum block chains**
- Medical use cases: image classification and segmentation for neurological diseases research



Numerical Methods and Simulations in Particle Theory

Modern day HEP requires high performance computing, relying on Monte Carlo simulations

- Mass Spectrum and Scattering in Low Energy Nuclear Physics
- Hadronic contributions to BSM Experimental Searches
- Event generation for Particle Collisions

Main focus is developing methodologies and algorithms that would allow us to address these questions using quantum computers, without relying on importance sampling

But not every physics problem is amenable to Monte Carlo simulation

- Nuclear Physics at Finite Density (sign problem)
- Interference effects in Parton Showers (must work at amplitude level)
- Transfer Phenomena (must work in real time)
- Baryonic Physics (signal to noise problem)

Thanks!

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