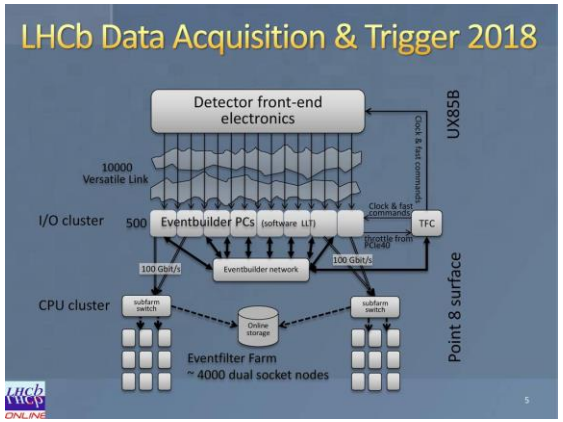
CERN QTI: Overview

Alberto Di Meglio

CERN

QUANTUM
TECHNOLOGY
INITIATIVE

LHC Experiments Computing Workloads



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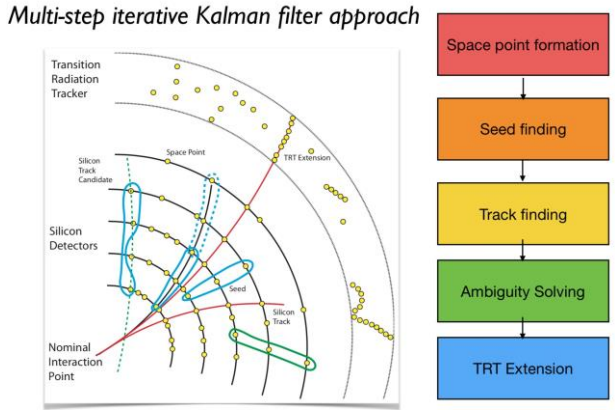
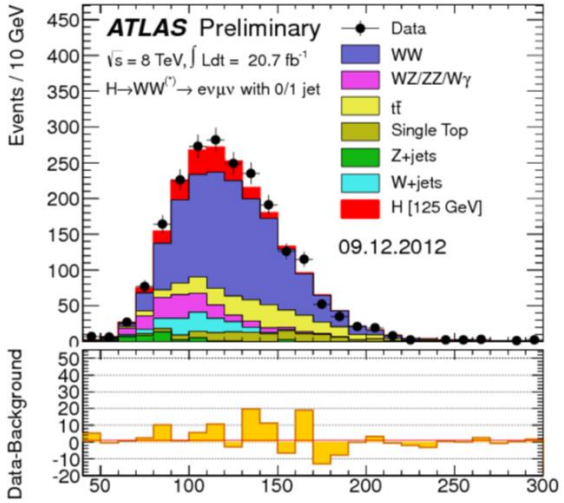
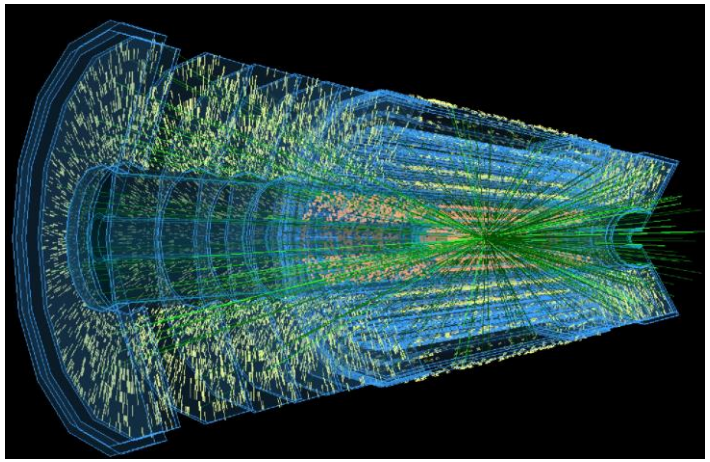
Data Acquisition



Track Reconstruction

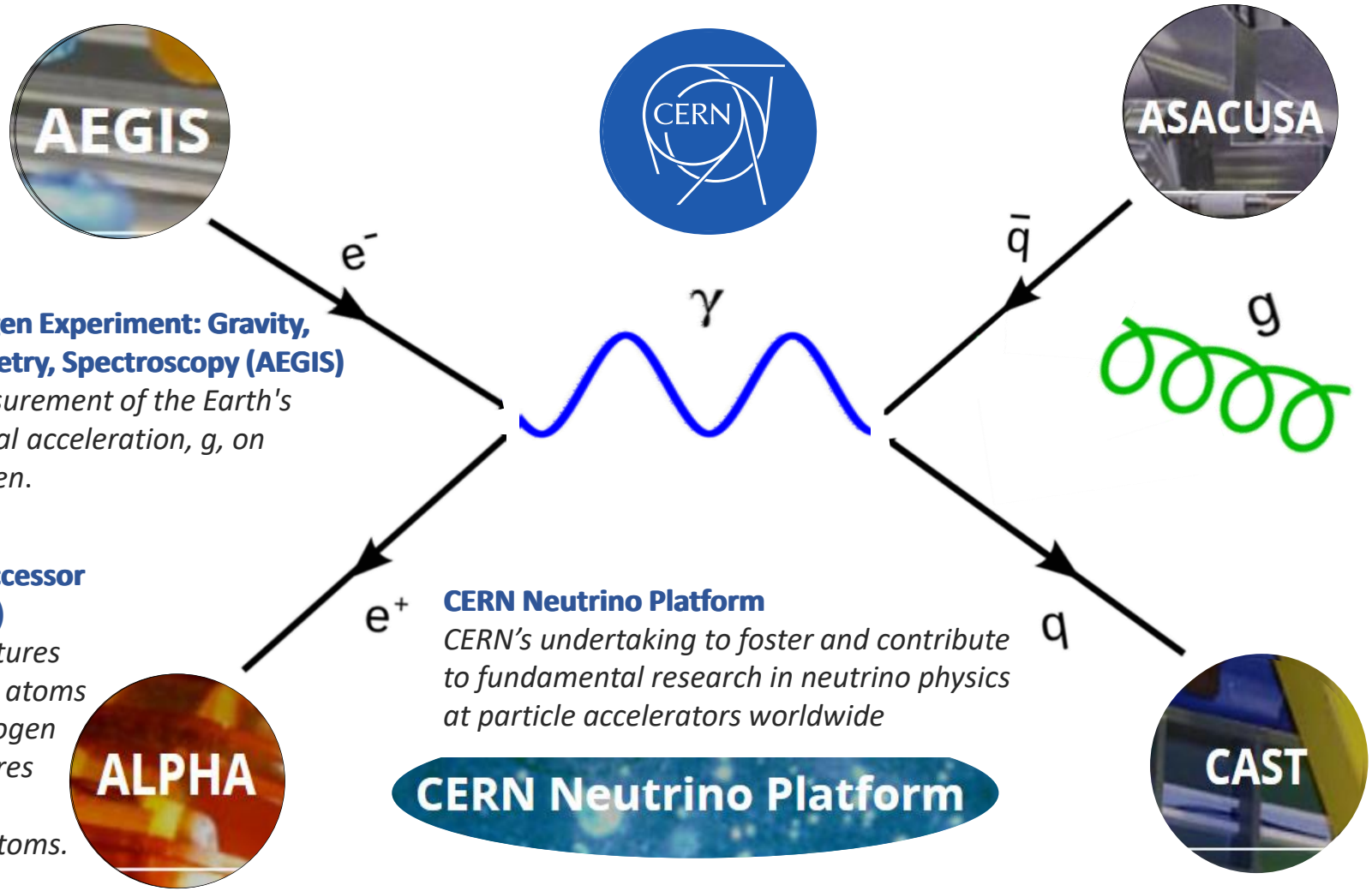


Data Analysis



Simulation

Non-LHC Experiments



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

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

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.

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

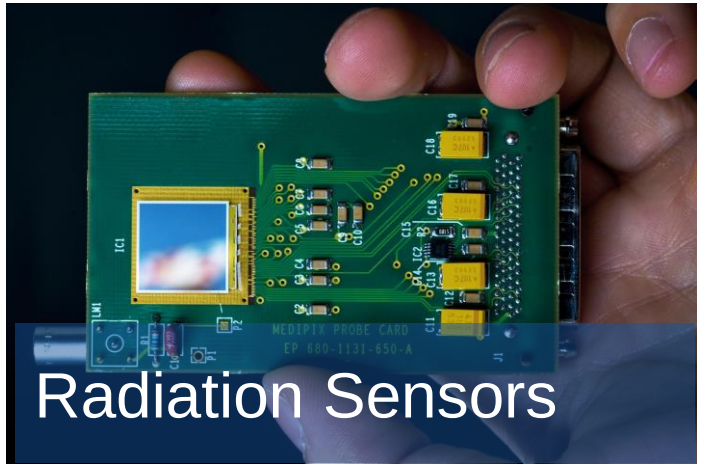
Lattice — theory inputs for nuclear and particle physics, first principle calculations of the low energy aspects of QCD, lattice as a formal tool for understanding QFTS

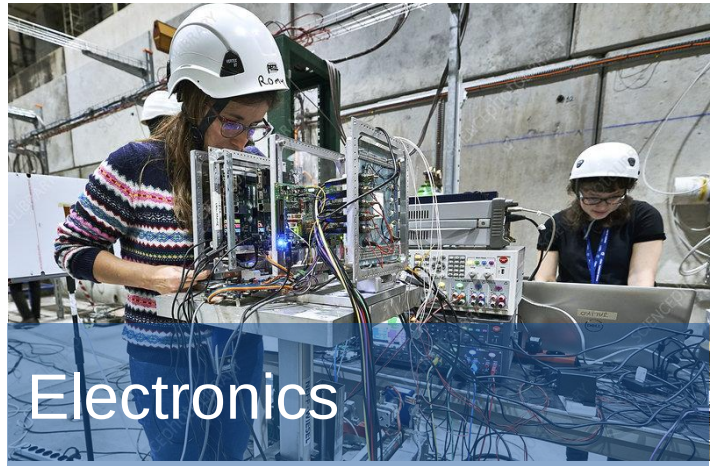
BSM — collider searches for BSM, dark matter model building, experimental signatures of dark matter, model building of new physics, BSM explanation of experimental anomalies

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

Engineering





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

T1 - Scientific and Technical Development and Capacity Building

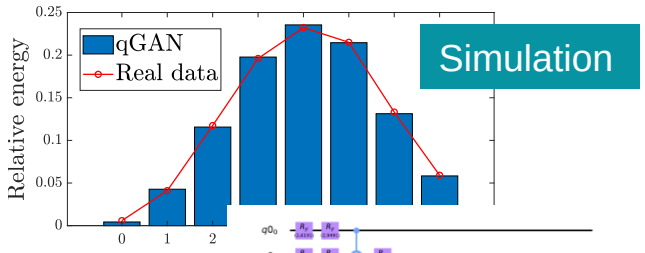
T3 - Community Building

T2 - Co-development

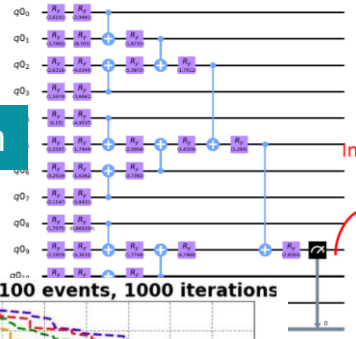
T4 - Integration with national and international initiatives and programmes

R&D Interests

Computing

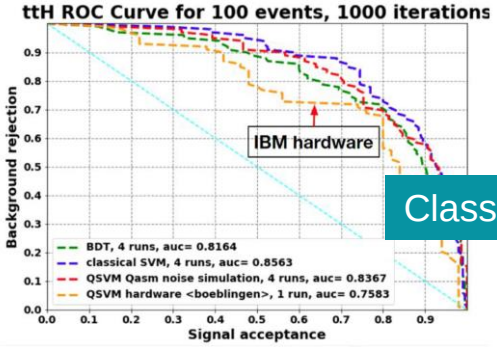


Simulation



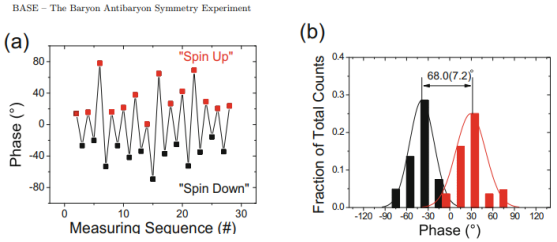
Reconstruction

Node Information



Classification

Sensing

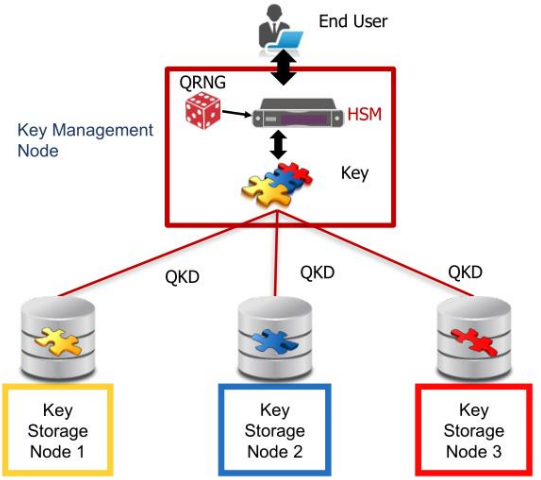


https://doi.org/10.1140/epjst/e2015-02607-4

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

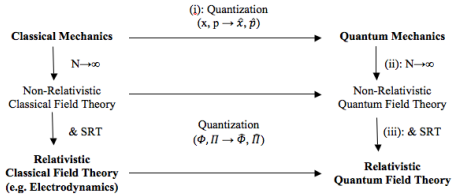
Future HEP Detectors

Communications

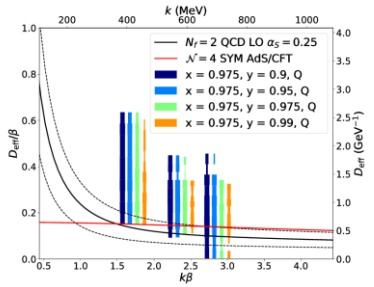


QKD infrastructures Quantum Internet

Theory



Quantum Field Theory



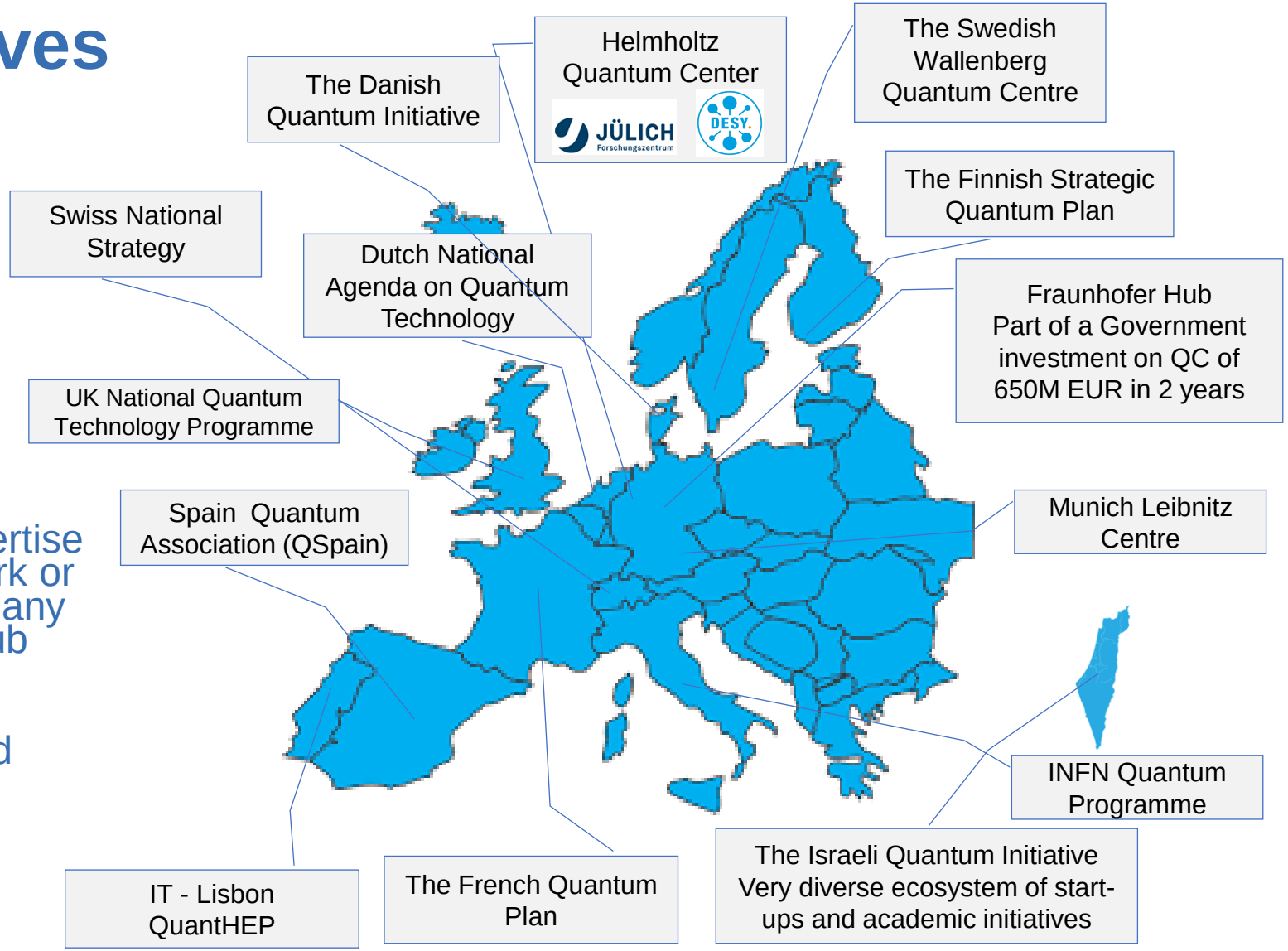
https://cds.cern.ch/record/2703396

Lattice QCD

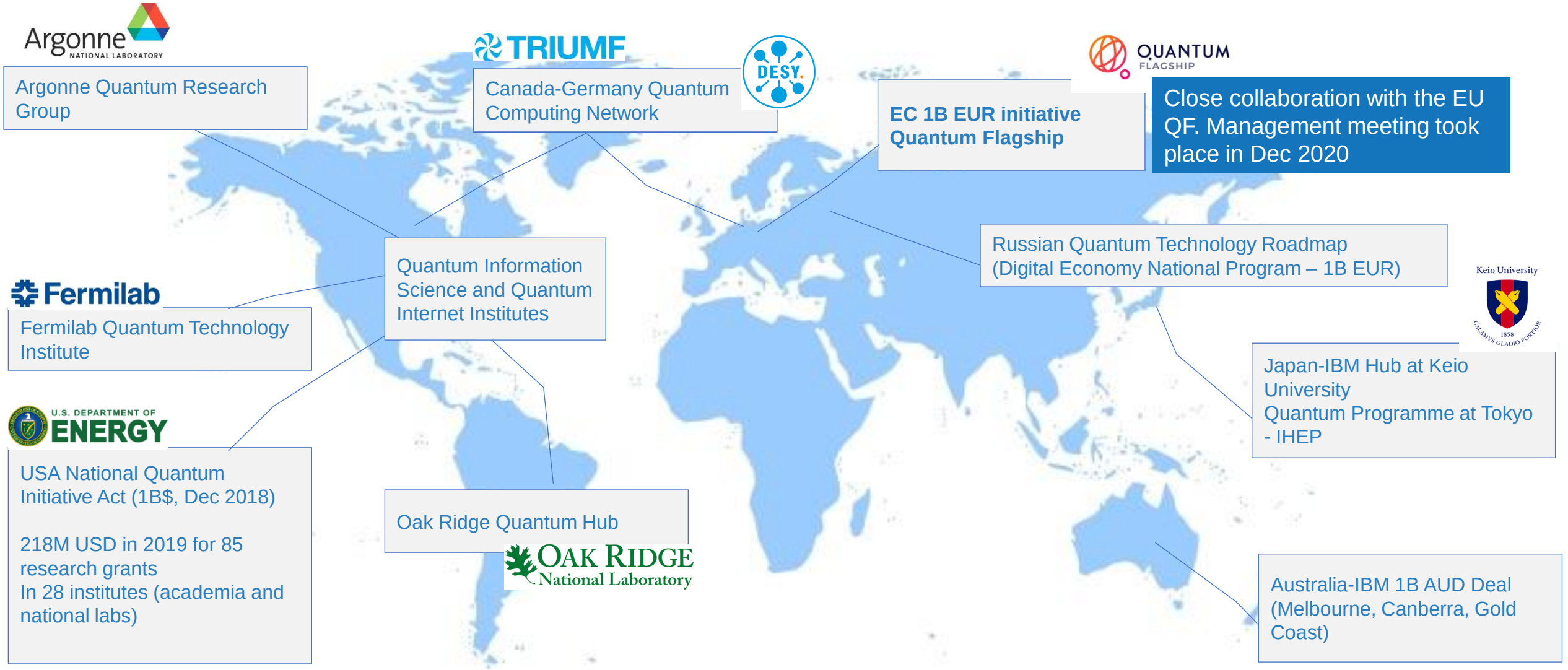
Many pilot projects already started as part of the **CERN openlab quantum** programme (https://openlab.cern/quantum)

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



Argonne Quantum Research Group

Canada-Germany Quantum Computing Network

EC 1B EUR initiative Quantum Flagship

Close collaboration with the EU QF. Management meeting took place in Dec 2020

Russian Quantum Technology Roadmap (Digital Economy National Program – 1B EUR)

Quantum Information Science and Quantum Internet Institutes

Fermilab Quantum Technology Institute

Japan-IBM Hub at Keio University
Quantum Programme at Tokyo - IHEP

USA National Quantum Initiative Act (1B$, Dec 2018)

218M USD in 2019 for 85 research grants
In 28 institutes (academia and national labs)

Oak Ridge Quantum Hub

Australia-IBM 1B AUD Deal (Melbourne, Canberra, Gold Coast)

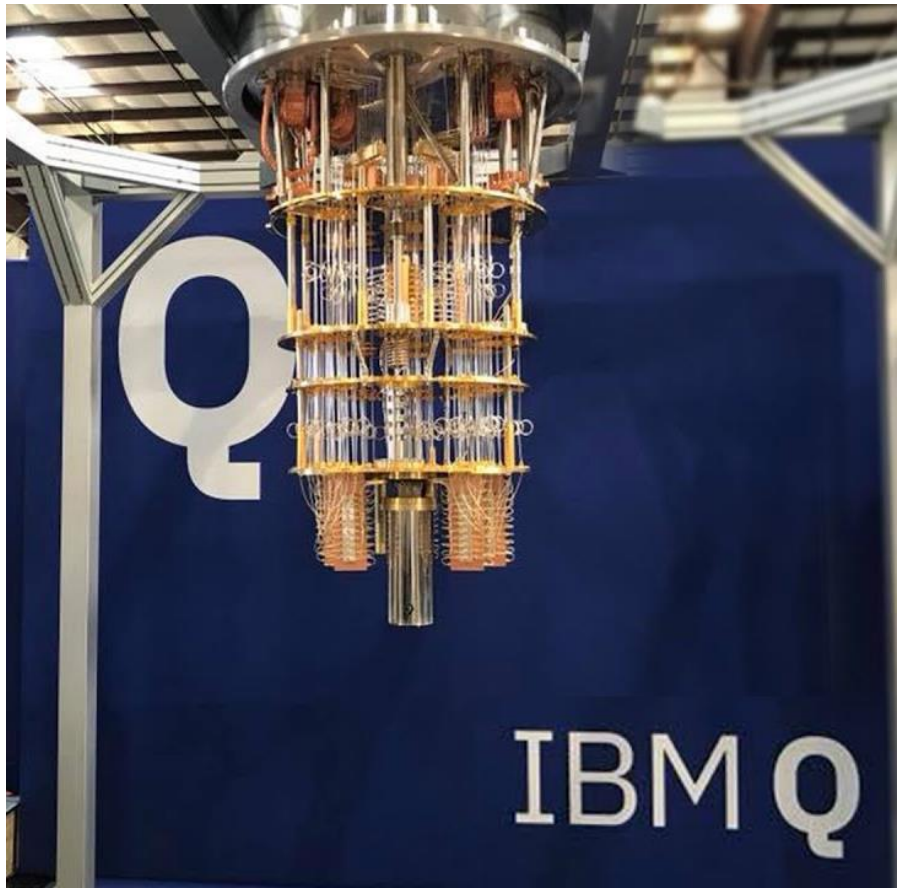
Who we are talking to

Organizations and Projects

Industry

Academia, Research Labs and Agencies

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)

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)

QML models implementations for NISQ

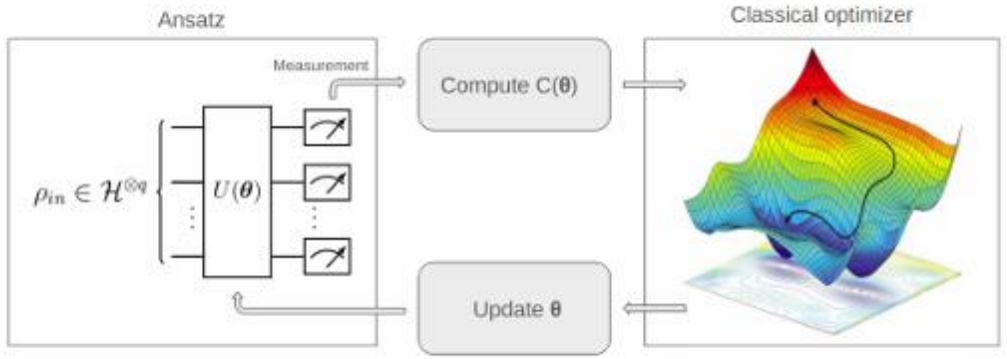
Variational algorithms - EXPLICIT

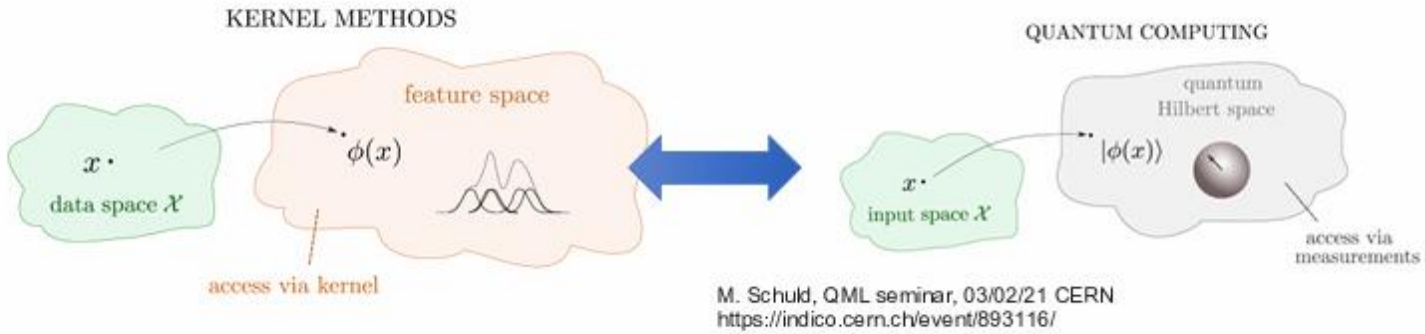
- Flexible parametric ansatz: design can leverage data symmetries[1]
- Can use **gradient-free** methods or **stochastic gradient-descent**
- **Data Embedding** can be **learned**
- **Better generalization[1]**

Kernel methods - IMPLICIT

- **Feature maps** as **quantum kernels**
- **Convex** losses, **global** minimum
- Identify kernel classes that relate to specific **data structures[3]**
- **Better accuracy[2]**

→ What is easiest to use/define?





M. Schuld, QML seminar, 03/02/21 CERN
https://indico.cern.ch/event/893116/

1-Bogatskiy, Alexander, et al. "Lorentz group equivariant neural network for particle physics." PMLR, 2020

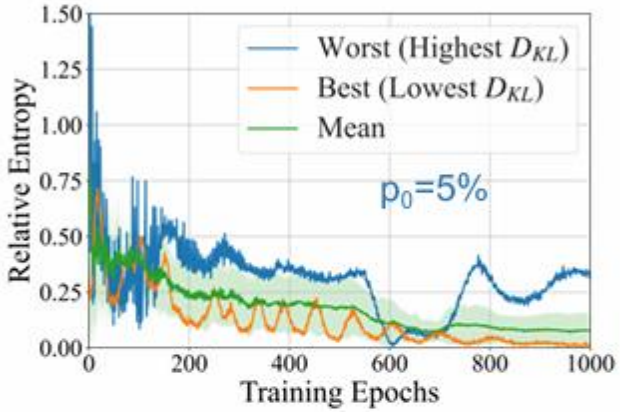
2-S.Jerbi at all., Quantum Machine Learning Beyond Kernel Methods https://arxiv.org/abs/2110.13162

3- Glick, Jennifer R., et al. "Covariant quantum kernels for data with group structure." arXiv:2105.03406 (2021)

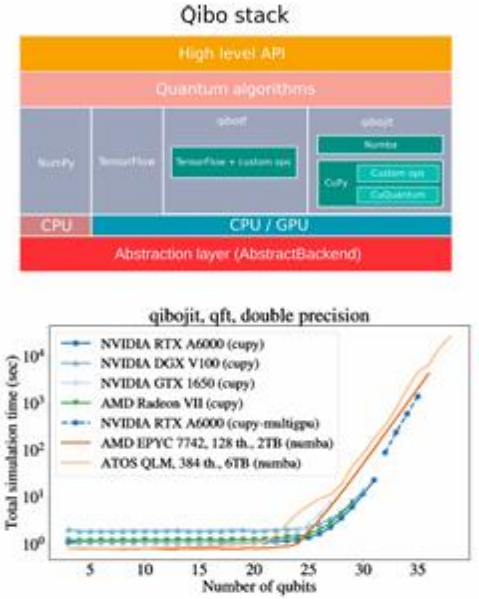
Do they really differ? Where to focus?

QC @ CERN

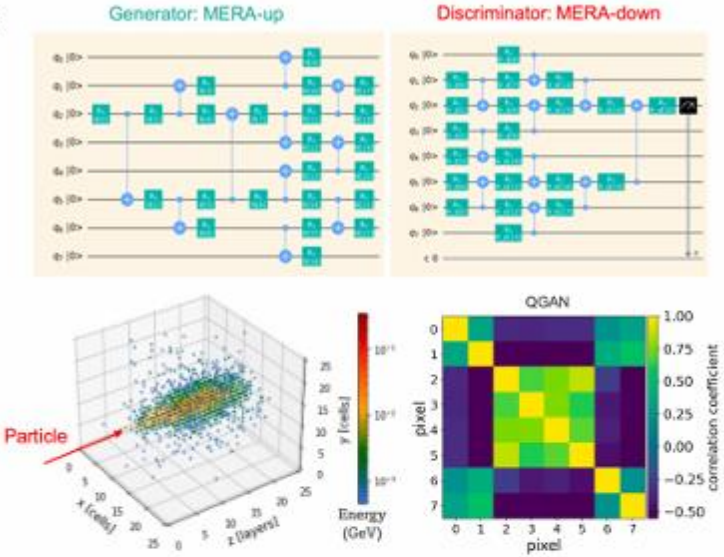
Borras, Kerstin, et al. "**Impact of quantum noise on the training of quantum Generative Adversarial Networks.**" *arXiv preprint arXiv:2203.01007* (2022).



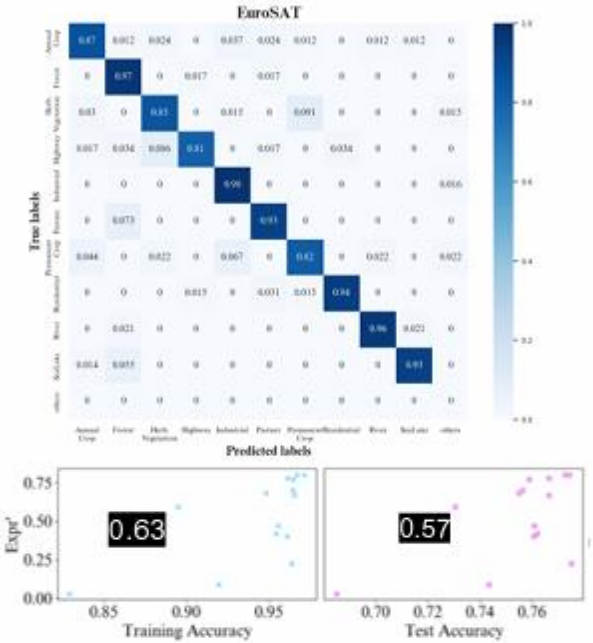
E.Stavros et all., **Quantum simulation with just-in-time compilation,** Quantum 2022



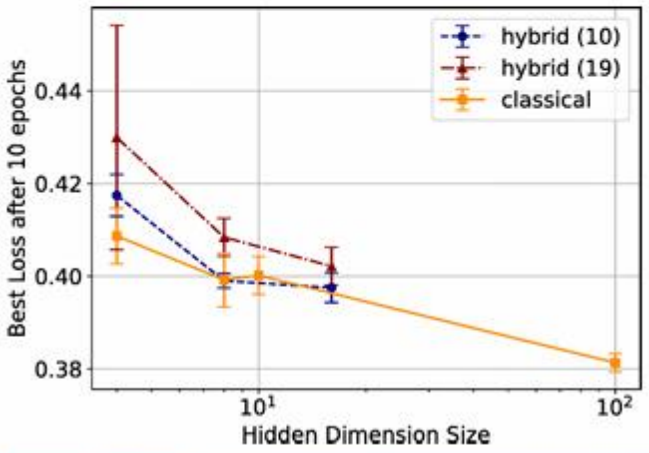
F.Rehm, **Full Quantum GAN Model for HEP Detector Simulations,** ACAT22



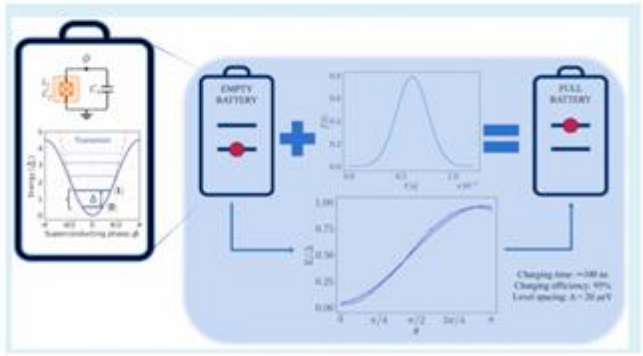
S.Chang, et all, **Hybrid Quantum-Classical Networks for Reconstruction and Classification of Earth Observation Images,** ACAT22



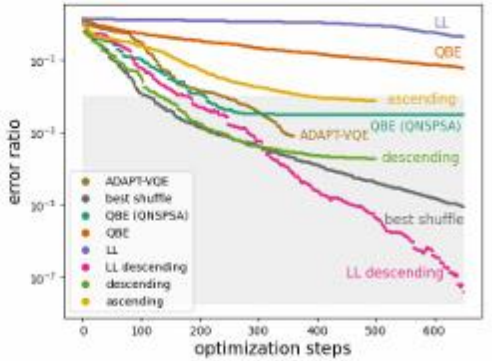
Tüysüz, Cenk, et al. "**Hybrid quantum classical graph neural networks for particle track reconstruction.**" *Quantum Machine Intelligence* 3.2 (2021): 1-20.



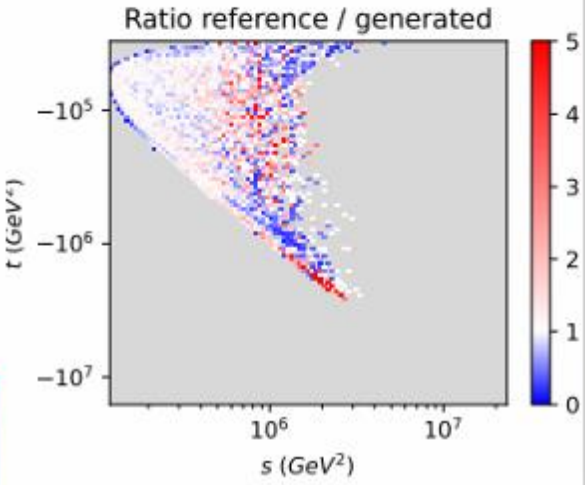
G. Gemme, M. Grossi et al, **IBM Quantum Platforms: A Quantum Battery Perspective**, *Batteries* ***8****, 43 (2022)*



O. Kiss, **Quantum computing of the 6Li nucleus via ordered unitary coupled cluster,** 10.1103/PhysRevC.106.034325

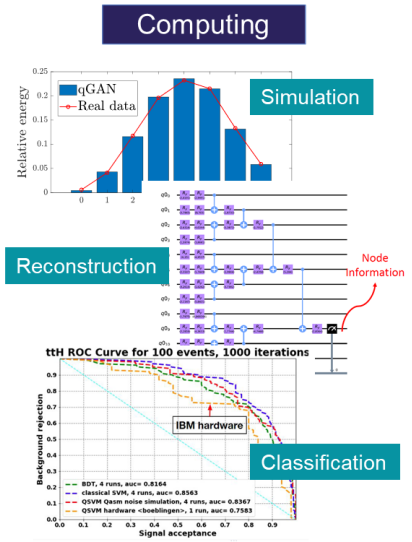


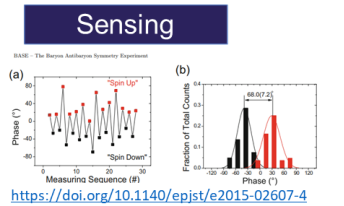
Bravo-Prieto, Carlos, et al. "**Style-based quantum generative adversarial networks for Monte Carlo events.**" *Quantum 2022*



Scientific Production

- **More than 20 projects in all four quantum areas**
- **More than 30 publications**
  - Many of them on peer-reviewed journals
- **More than 20 talks and presentations at conferences and workshops**





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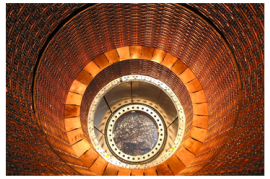
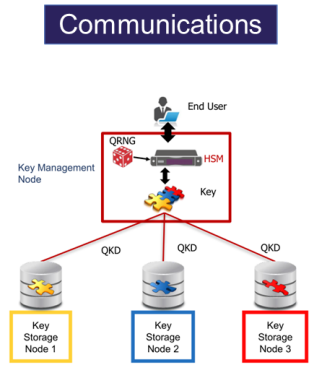
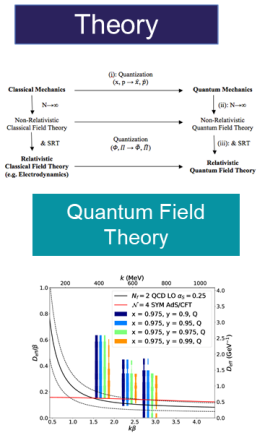
Low-energy experiments, quantum states measurements, nano-technologies



Future HEP Detectors



QKD infrastructures Quantum Internet



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

Lattice QCD

International Conference on Quantum Technologies for High-Energy Physics (QT4HEP22)

1–4 Nov 2022
CERN
Europe/Zurich timezone
There is a live webcast for this event.

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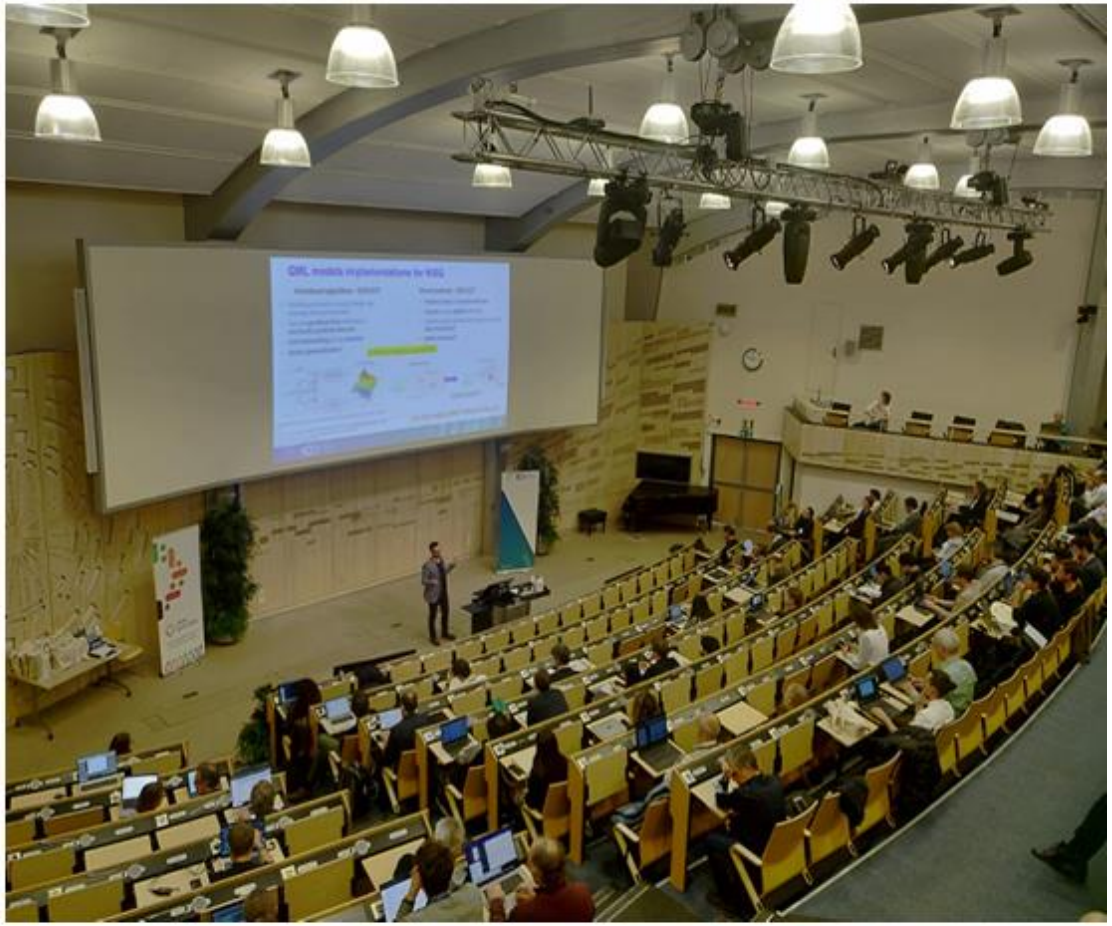
Contact

QT4HEP-conference@c...

Registration deadline extended until Friday, 28 October for the International Conference on Quantum Technology for High-Energy Physics, which will be hosted at CERN on 1–4 November 2022.

Following CERN's successful workshop on quantum computing in 2018, this is the first edition of the #QT4HEP conference taking place to further investigate the nascent quantum technology and its great promise to support scientific research.

Bringing the whole community together, we aim to foster common activities and knowledge sharing, discuss the recent developments in the quantum science field and keep looking for activities within HEP — and beyond — that can most benefit from the application of quantum technologies.



White paper on Quantum Computing for HEP

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

Alberto Di Meglio[8*], Karl Jansen[5], Ivano Tavernelli[3], Constantia Alexandrou[1], Srinivasan Arunachalam[3], Christian W Bauer[4], Kerstin Borras[5,6], Stefano Carrazza[7,8], Arianna Crippa[5,29], Vincent Croft[9], Roland de Putter[3], Andrea Delgado[10], Vedran Dunjko[9], Elias Fernández-Combarro[11], Elina Fuchs[8], Lena Funcke[12], Jay Gambetta[3], Daniel González Cuadra[13,14], Michele Grossi[8], Zoe Holmes[15], Stefan Kühn[5,2], Denis Lacroix[16], Randy Lewis[17], Donatella Lucchesi[18], Miriam Lucio Martinez[19], Federico Meloni[5], Antonio Mezzacapo[3], Simone Montangero[20], Lento Nagano[21], Voica Radescu[3], Enrique Rico Ortega[22], Alessandro Roggero[23,24], Julian Schuhmacher[3], Joao Seixas[25], Pietro Silvi[20], Panagiotis Spentzouris[26], Francesco Tacchino[3], Kristan Temme[3], Koji Terashi[21], Jordi Tura[9], Cenk Tüysüz[5,29], Sofia Vallecorsa[8], Uwe-Jens Wiese[27] and Jinglei Zhang[28]

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Abstract

Quantum computers offer a fascinating path for a paradigmatic change of computing with the potential of a quantum advantage. The rapid development of hardware devices with various realizations of qubits allows already now to execute 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

Successful QT4HEP Conference in November, more than 250 attendees. A **working group on Quantum technology for HEP has been formed** with participation from HEP Institutes in EU, US, Japan and other countries showing the impact that CERN is having in the field via the QTI activities.

Working on a joint paper across the HEP community to be published in Spring 2023. More than 40 contributors from HEP institutes in EU, US, and Japan

Next steps

- Initial exploration has been very successful
- We need to move to the next level → Integration within large-scale computing infrastructures

- Large investments in the CERN Member States and LHC experiments members on HPC and Quantum
- The EC is implementing a strategy based on the establishment of a number of pre-exascale and exascale HPC centres – coordinated through the EuroHPC collaboration. Work to assess the use of HPC for HEP is underway
- The EU exascale centres have recently been selected to co-host also the future Quantum computing centres – coordinated through the EuroQCS programme

- CERN interests is in collaborating with the EuroHPC+EuroQCS centres to co-develop hybrid classic/quantum accelerated algorithms

Knowledge Transfer Opportunities

- Measurement & control of quantum-scale systems
- Particle traps technologies
- Excited atoms, ions
- Picosecond Synchronisation
- FPGAs for quantum simulators
- Digital Low-Level Radio Frequency (LLRF) control systems
- Cryogenic system design, measurement & control
- Vacuum system design & control (HV, UHV, XHV)
- Thin film coatings for high-performance applications
- Laser devices

https://kt.cern/competences/cern-tech-quantum-systems

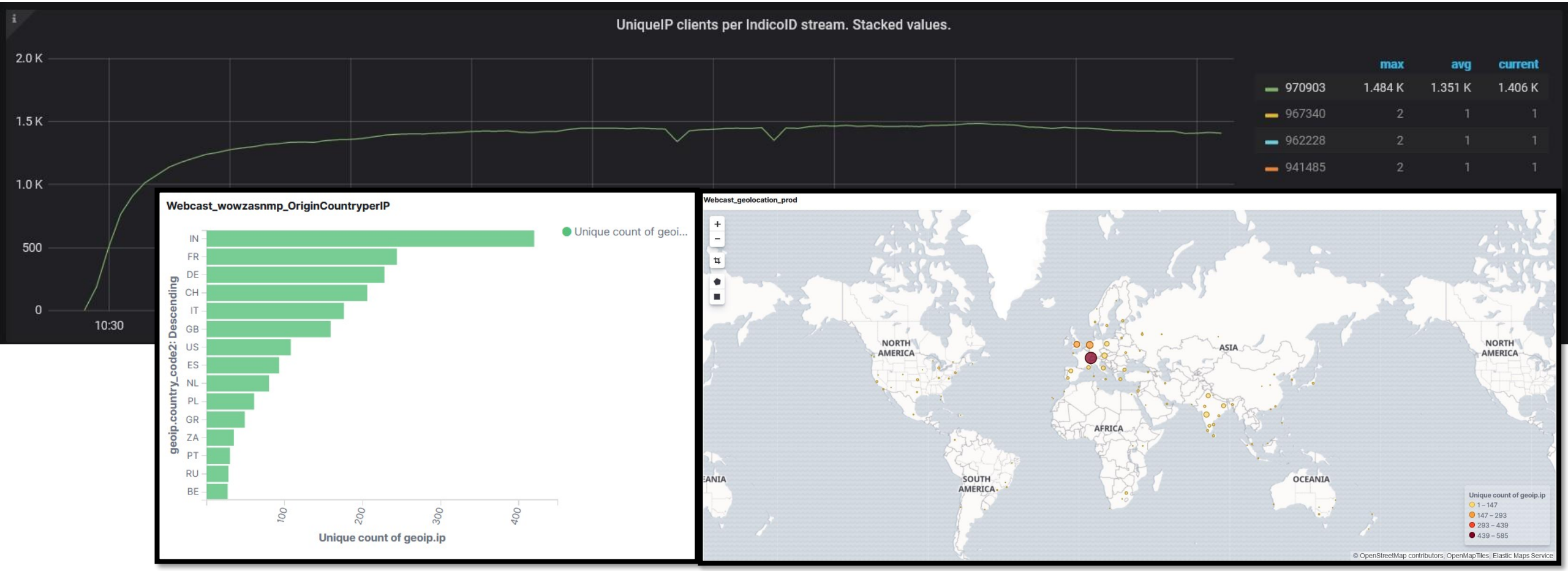
Education Programme

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

“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)



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.

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