CERN

Quantum Computing for High Energy Physics

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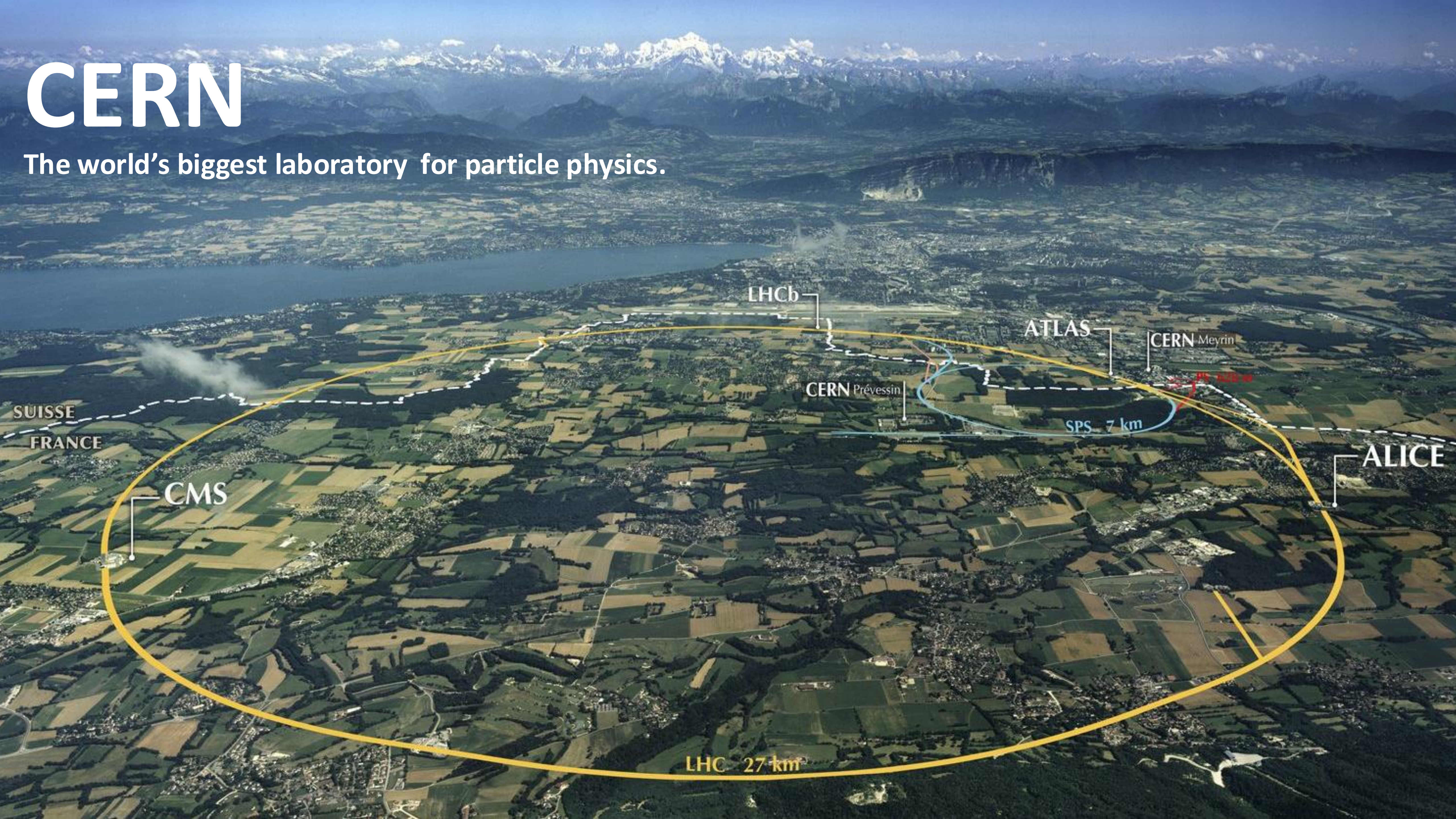
Sofia Vallecorsa
CERN QTI Coordinator
CERN

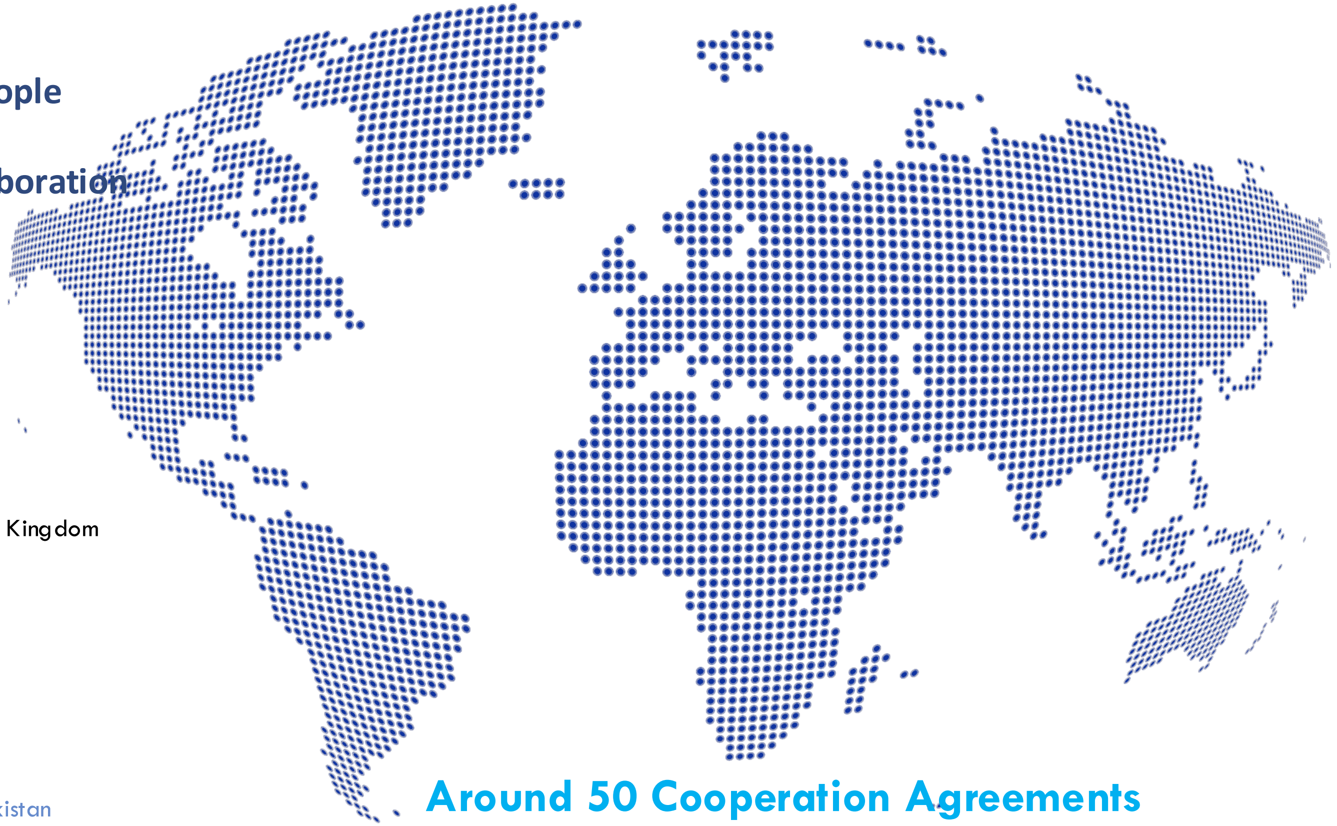


CERN
The world’s biggest laboratory for particle physics.
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Science for peace

CERN was founded in 1954 with 12 European Member States

Today, CERN is a laboratory for people around the world and a model for open and inclusive collaboration



CERN's annual budget is 1200 MCHF (equivalent to a medium-sized European university)

As of 31 December 2023
Employees:
2666 staff, 1002 graduates
Associates:
12 370 users, 1513 others

24 Member States

Austria – Belgium – Bulgaria – Czech Republic
Denmark – Estonia – Finland – France – Germany
Greece – Hungary – Israel – Italy – Netherlands
Norway – Poland – Portugal – Romania – Serbia
Slovakia – Spain – Sweden – Switzerland – United Kingdom

2 Associate Member States

in the pre-stage to membership

Cyprus – Slovenia

8 Associate Member States

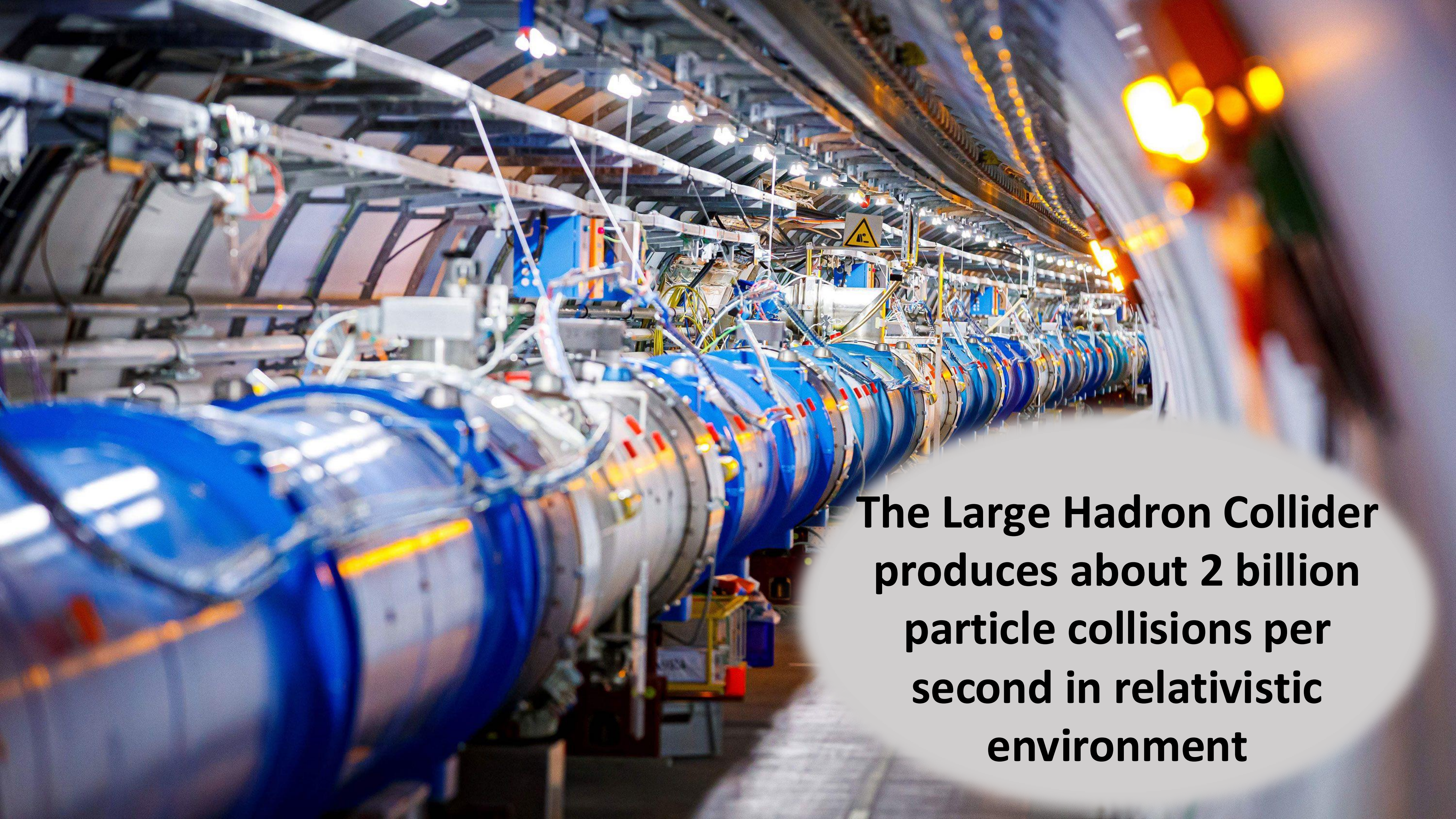
Brazil – Croatia – India – Latvia – Lithuania – Pakistan
Türkiye – Ukraine

6 Observers

Japan – Russia (suspended) – USA
European Union – JINR (suspended) – UNESCO

Around 50 Cooperation Agreements with non-Member States and Territories

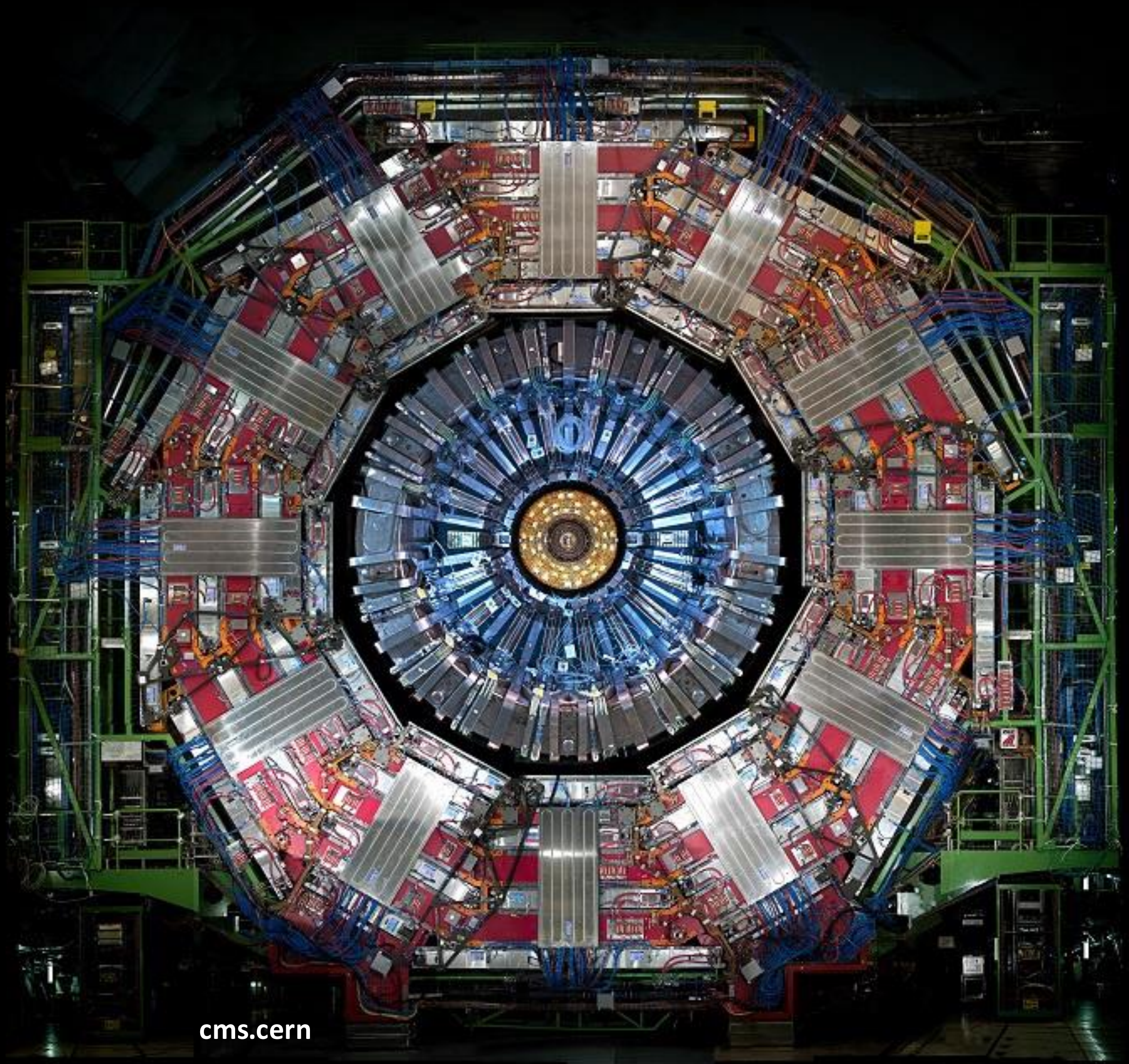
Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Bolivia – Bosnia and Herzegovina
Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Honduras – Iceland – Iran – Jordan
Kazakhstan – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco – Nepal – New Zealand
North Macedonia – Palestine – Paraguay – People's Republic of China – Peru – Philippines – Qatar – Republic of Korea
Saudi Arabia – Sri Lanka – South Africa – Thailand – Tunisia – United Arab Emirates – Vietnam


The Large Hadron Collider produces about 2 billion particle collisions per second in relativistic environment

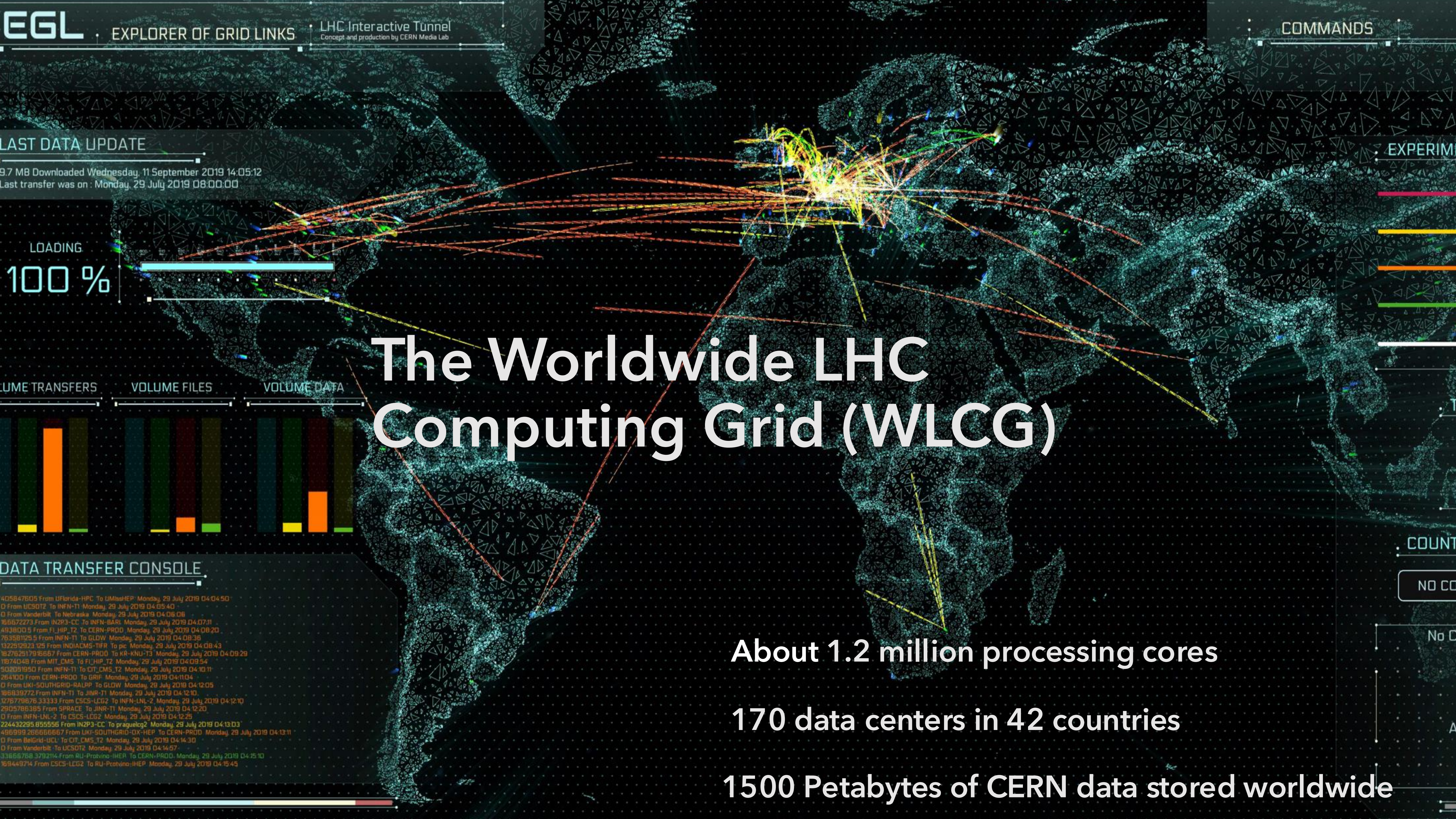
Detectors like 3D cameras

The energy of the colliding particles is converted into new particles.

Detectors “take” 40 million pictures per second, of which 1000 are selected and recorded.



cms.cern

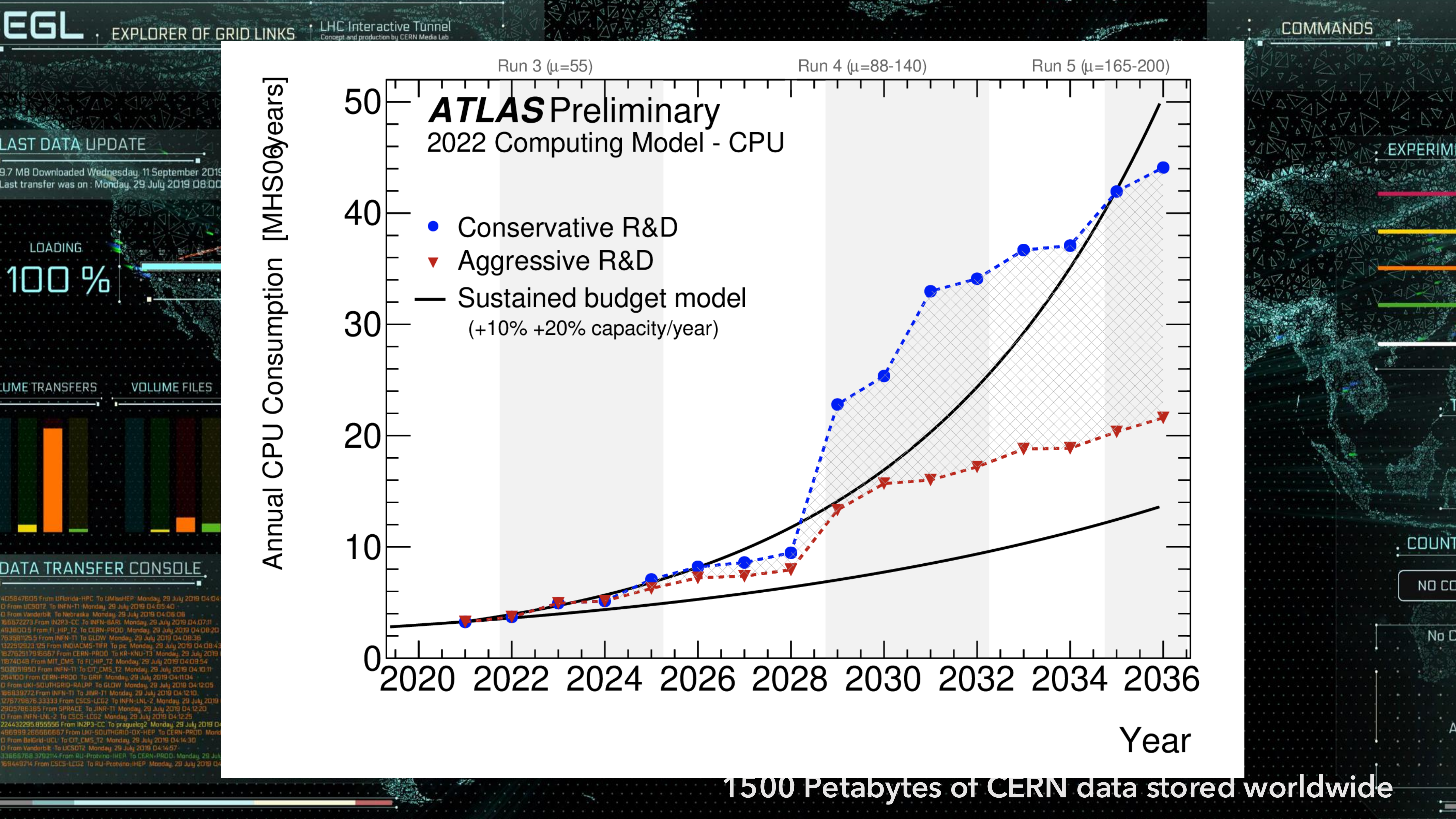


The Worldwide LHC Computing Grid (WLCG)

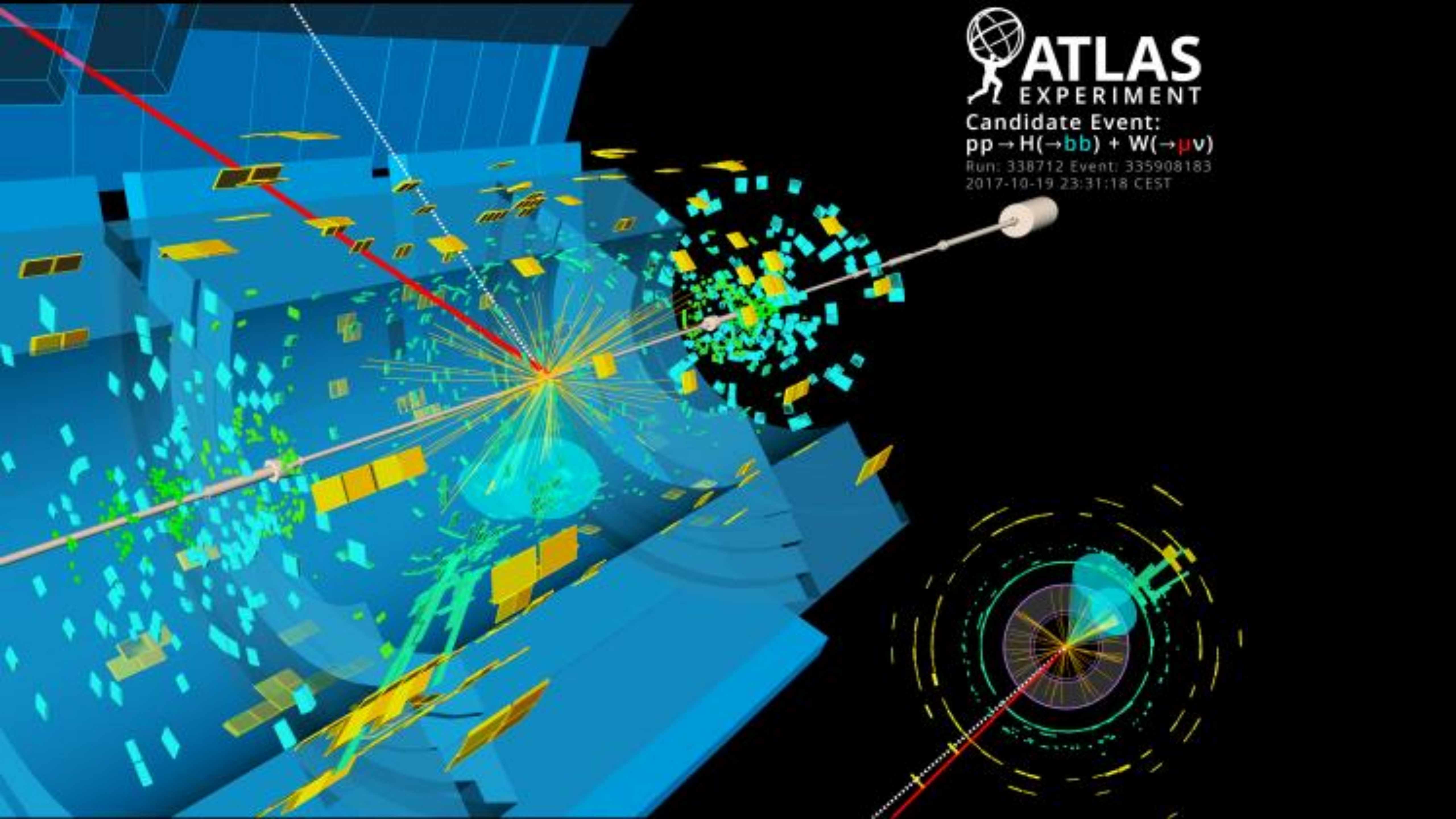
About 1.2 million processing cores

170 data centers in 42 countries

1500 Petabytes of CERN data stored worldwide



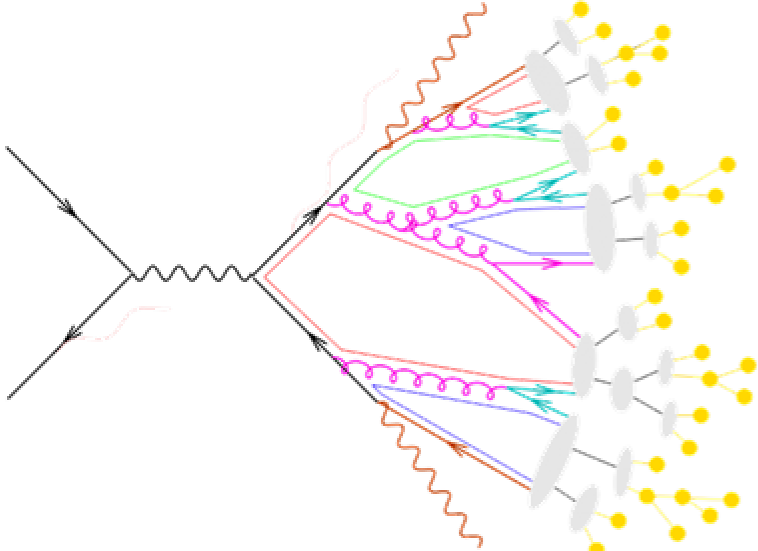
1500 Petabytes of CERN data stored worldwide


ATLAS
EXPERIMENT
Candidate Event:
pp → H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST

Theory and simulations challenges

- We are interested **in out-of equilibrium and real-time dynamic problems**

  (scattering, thermalisation or dynamics after quenches)
- **Complex equation of states and phase diagrams (QCD)**
- **Standard Monte Carlo solutions are two expensive or fail entirely**



Ex. **Phase space sampling for multi-jet @HL-LHC** becomes unfeasible

Process $W^{+}+$	5j	6j*	7j*	8j†
RAM Usage	189 MB	484 MB	1.32 GB	1.32 GB
Init/startup time	3m5s / 1s	24m52s / 5s	3h6m / 18s	5h55m / 20s
Integration time	128×4h38m	256×13h53m	512×19h0m	1024×23h8m
MC uncertainty	1.0%	0.99%	2.38%	4.68%
Unweighting eff	$9.56 \cdot 10^{-5}$	$7.66 \cdot 10^{-5}$	$7.20 \cdot 10^{-5}$	$7.51 \cdot 10^{-5}$
10k evts	24h 40m	2d 11h	10d 15h	78d 1h

Numbers generated on dual 8-core Intel® Xeon® E5-2660 @ 2.20GHz

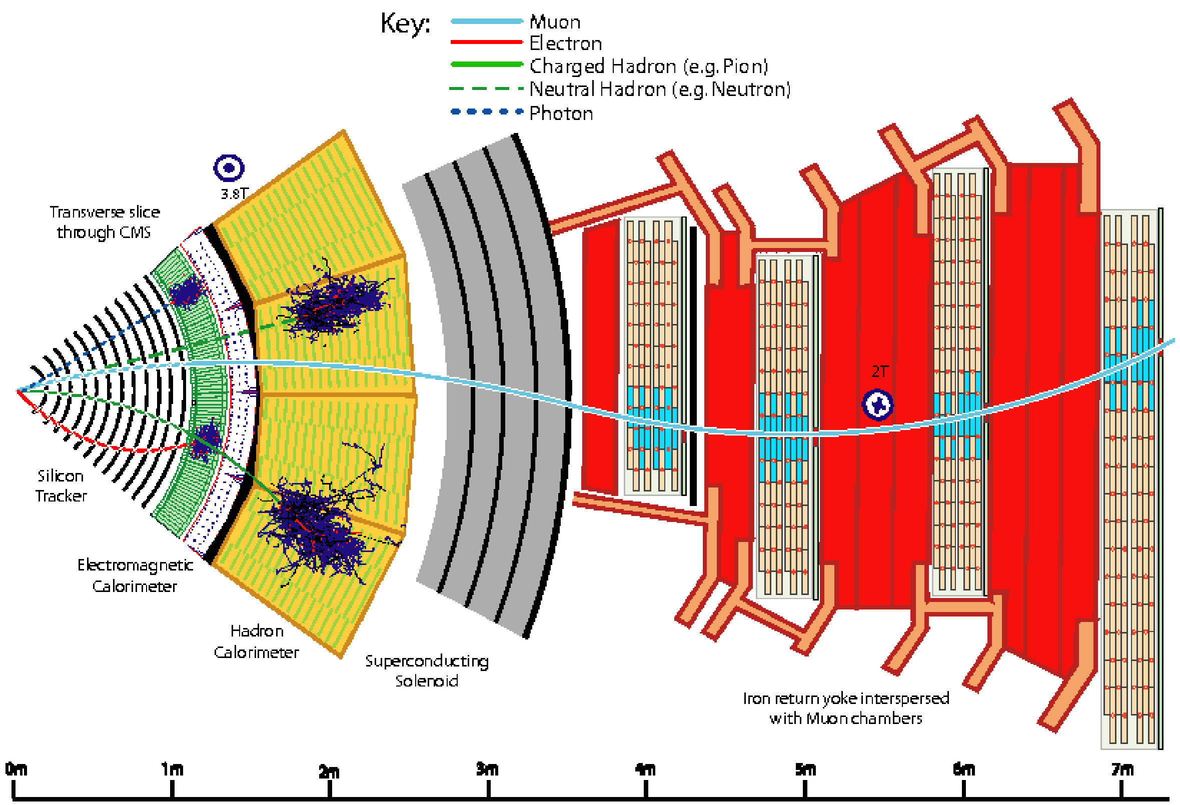
*,† Number of quarks limited to ≤6/4

Time and memory usage (Sherpa 3.x.y + HDF5) (H. Schulz 2018)

Experimental data processing challenges

Study fundamental interactions from experimental data which is:

- **Classical**, including:
  - **«Physics effects»**, *particle interaction with materials*
  - **«Detector effects»**, *data acquisition systems and software*
- **Big (aka Big Data):**
  - **Large** *(TB)* **multi-dimensional data sets** *(hundres of features per sample).*
- **Complex :**
  - **Multiple simultaneous collisions** *(up to hundreds in a few years).*
  - **Multi-structured information** (*Combination of information of different detectors).*
  - **Large dynamical ranges** (orders of magnitude)



The ATLAS Collaboration. **Observation of quantum entanglement with top quarks at the ATLAS detector.** *Nature* 633, 542–547 (2024). https://doi.org/10.1038/s41586-024-07824-z

The highest energy observation of entanglement

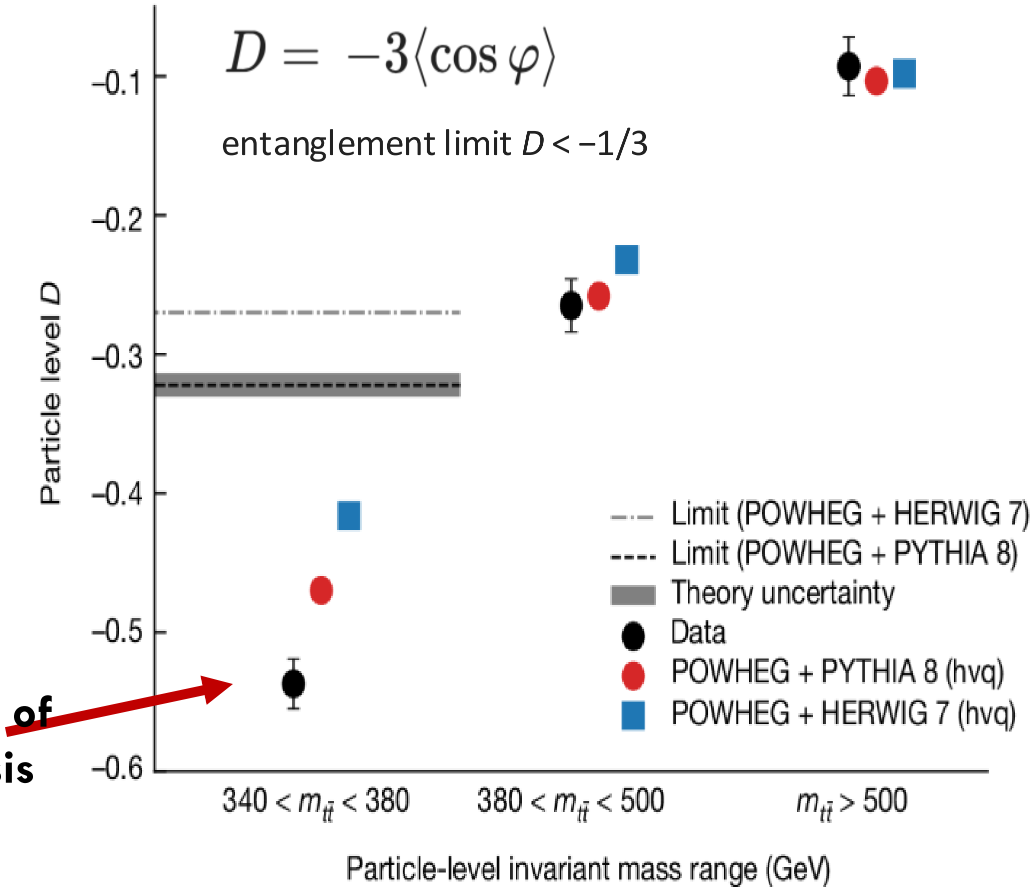
Spin entanglement in top- antitop-quark pairs measured at 13 TeV by the ATLAS detector at the LHC

Top lifetime ($\sim 10^{-25}$ s) is shorter than both hadronization ($\sim 10^{-24}$ s) and spin decorrelation ($\sim 10^{-21}$ s) timescales.

- **Top spin information is transferred to decay products.**
- **Direct entanglement observation** through measurement of single observable D built from **angle (ϕ)** between the leptons in the parent top- and antitop-quark rest frames.

Result is more than five standard deviations from scenarios without entanglement

Analysis complexity due to primarily to **uncertainty on internal degrees of freedom in the initial state, parton shower simulation restricted analysis phase space**



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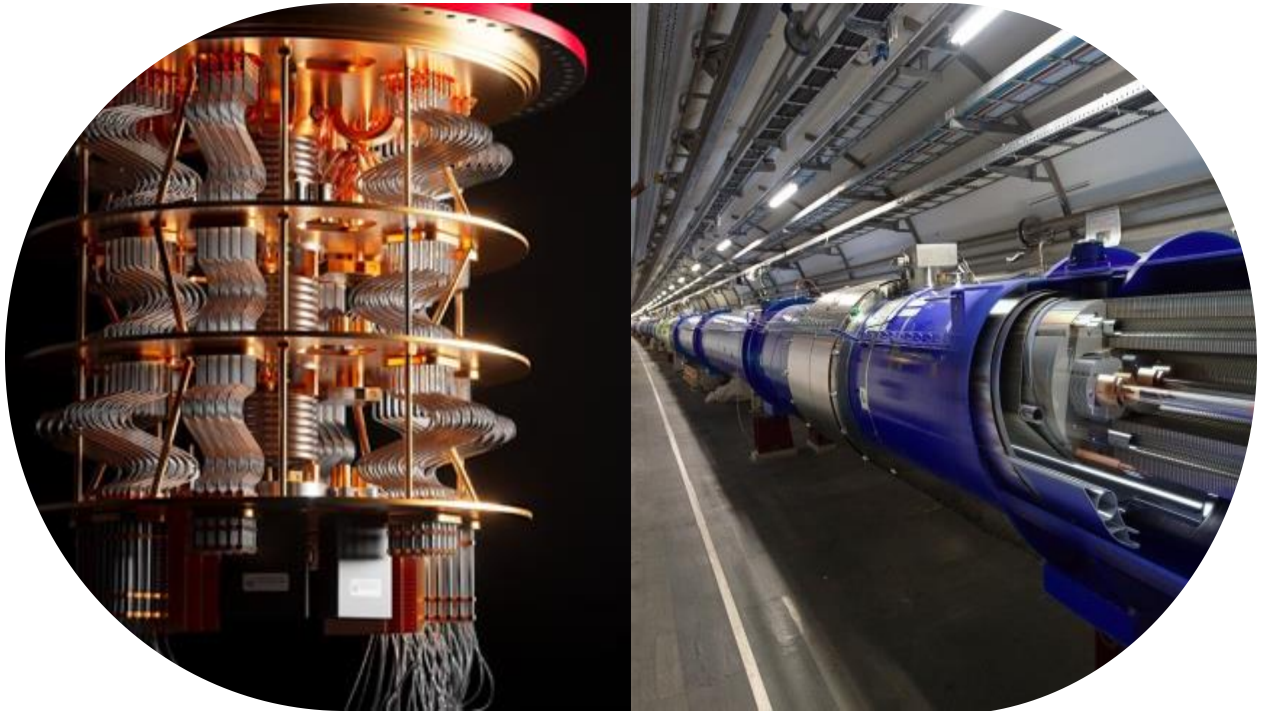
How does CERN engage in Quantum Technologies?

QT4HEP

Develop QT useful to the CERN scientific programme

Integrate CERN with future quantum infrastructure



HEP4QT

Extend and share technologies available at CERN

Boost development and adoption of QT beyond CERN

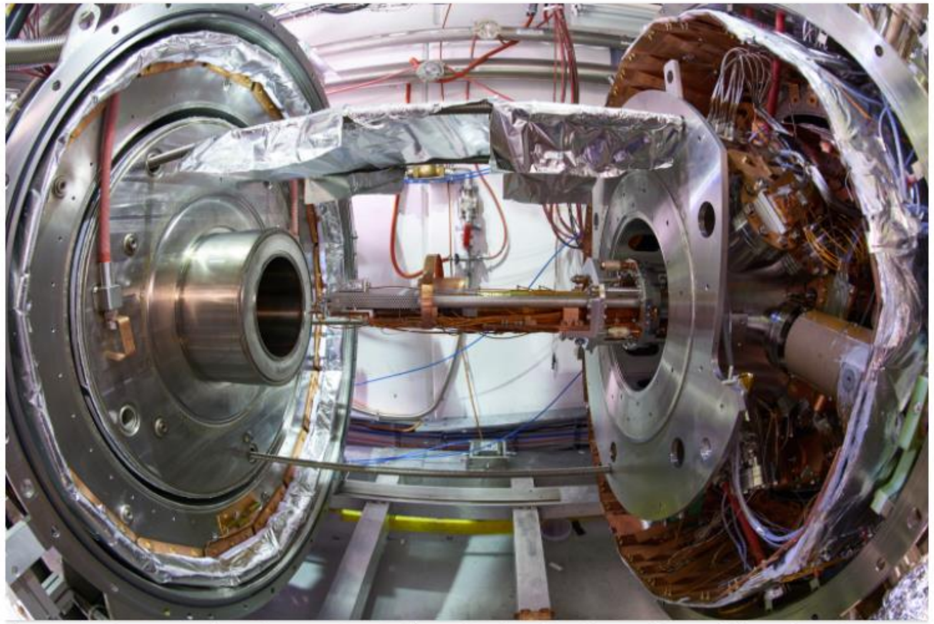
The CERN QTI launched in 2020

Voir en français

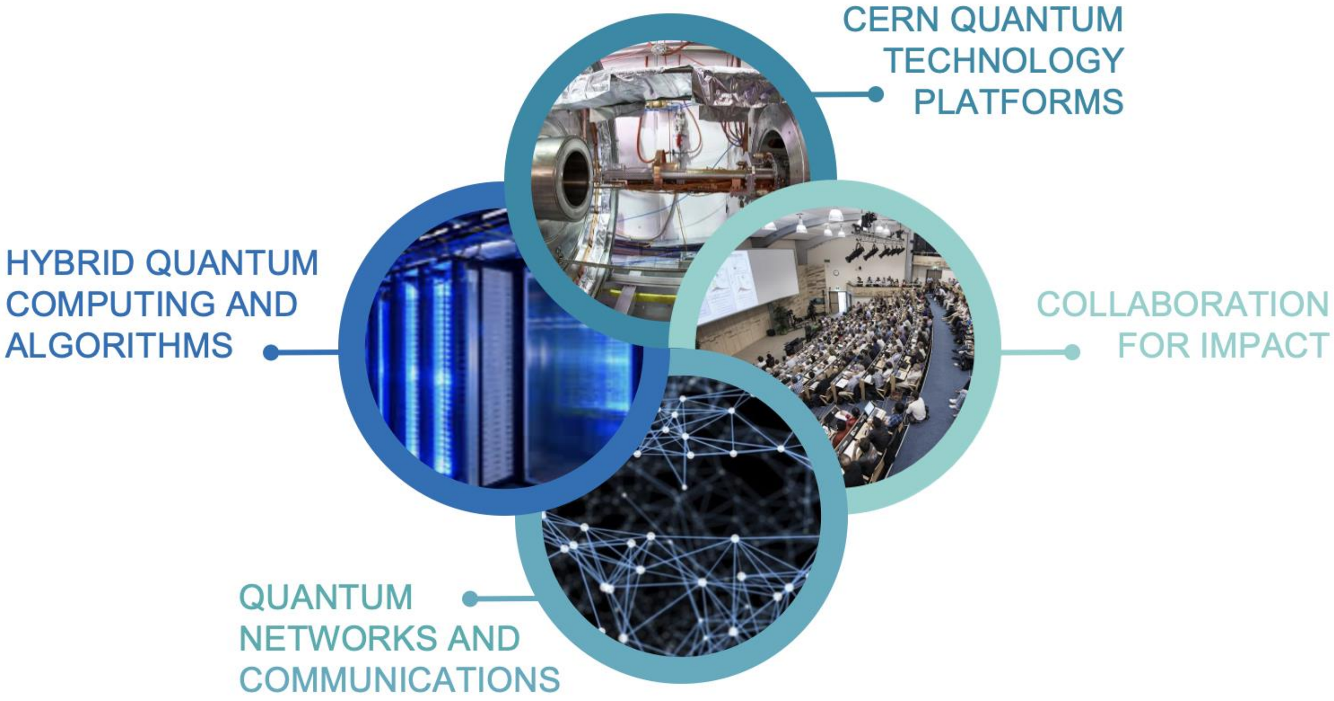
CERN meets quantum technology

The CERN Quantum Technology Initiative will explore the potential of devices harnessing perplexing quantum phenomena such as entanglement to enrich and expand its challenging research programme

30 SEPTEMBER, 2020 | By Matthew Chalmers



The AEgIS 1T antimatter trap stack. CERN's AEgIS experiment is able to explore the multi-particle entangled nature of photons from positronium annihilation, and is one of several examples of existing CERN research with relevance to quantum technologies. (Image: CERN)



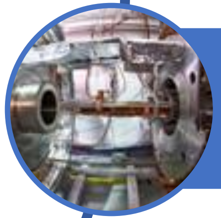
QTI objectives toward practical quantum technologies

Integrate quantum computers within High Energy Physics computing model

- Develop **hybrid algorithms for realistic applications**
- Contribute to infrastructure development

Make CERN a node of the future European network infrastructure

- Design **Quantum Network demonstrators** incorporating CERN technologies
- Benchmark **communication protocols in realistic use cases**



Develop next generation detectors for fundamental physics

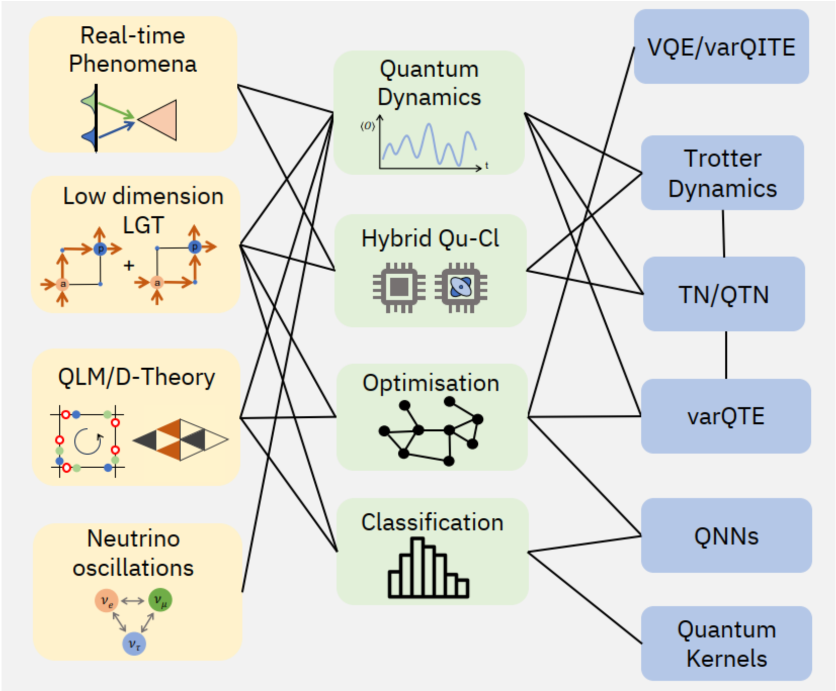
- Develop CERN accelerators technologies for quantum sensing and computing

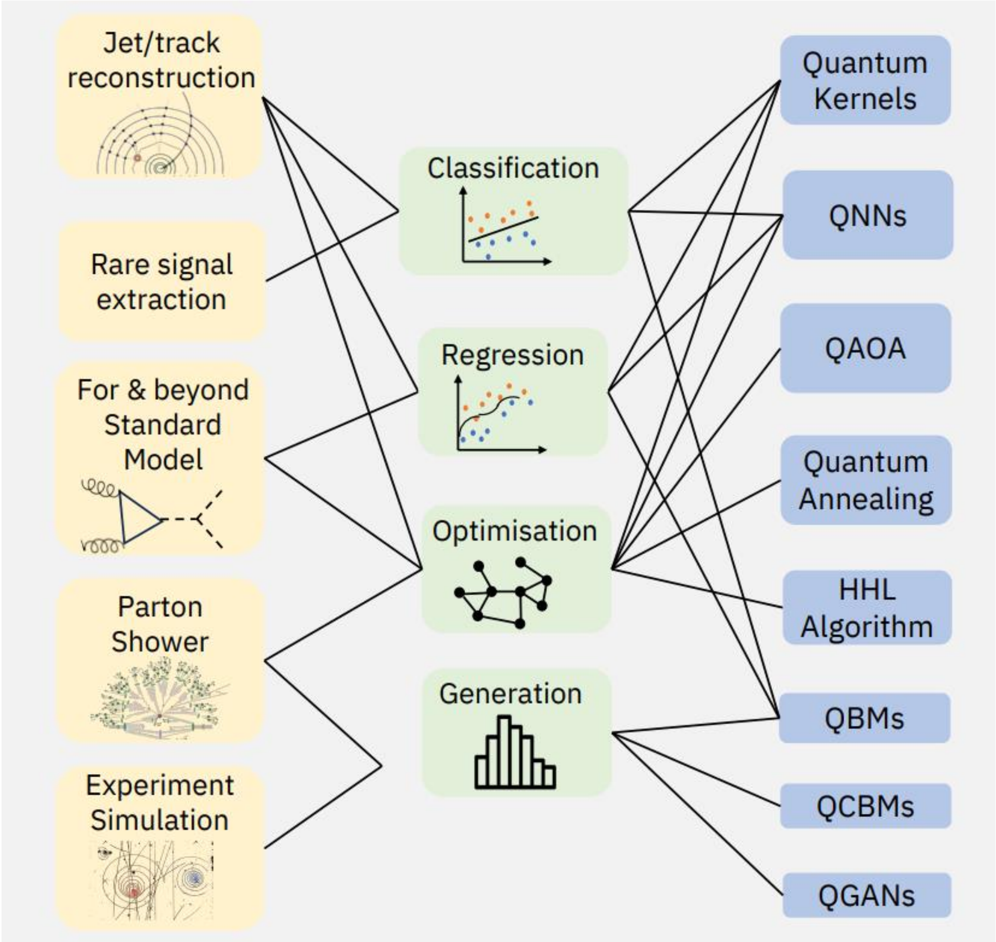
Join the broader quantum ecosystem to multiply impact

- Setup co-development partnerships with companies, institutes and other initiatives

Fostered a expert community studying usability of Quantum Computing for High Energy Physics

White Paper on a realistic roadmap in experimental and theoretical physics *PRX Quantum 5.3 (2024): 037001.*





QTI Quantum Computing research program

Algorithms:

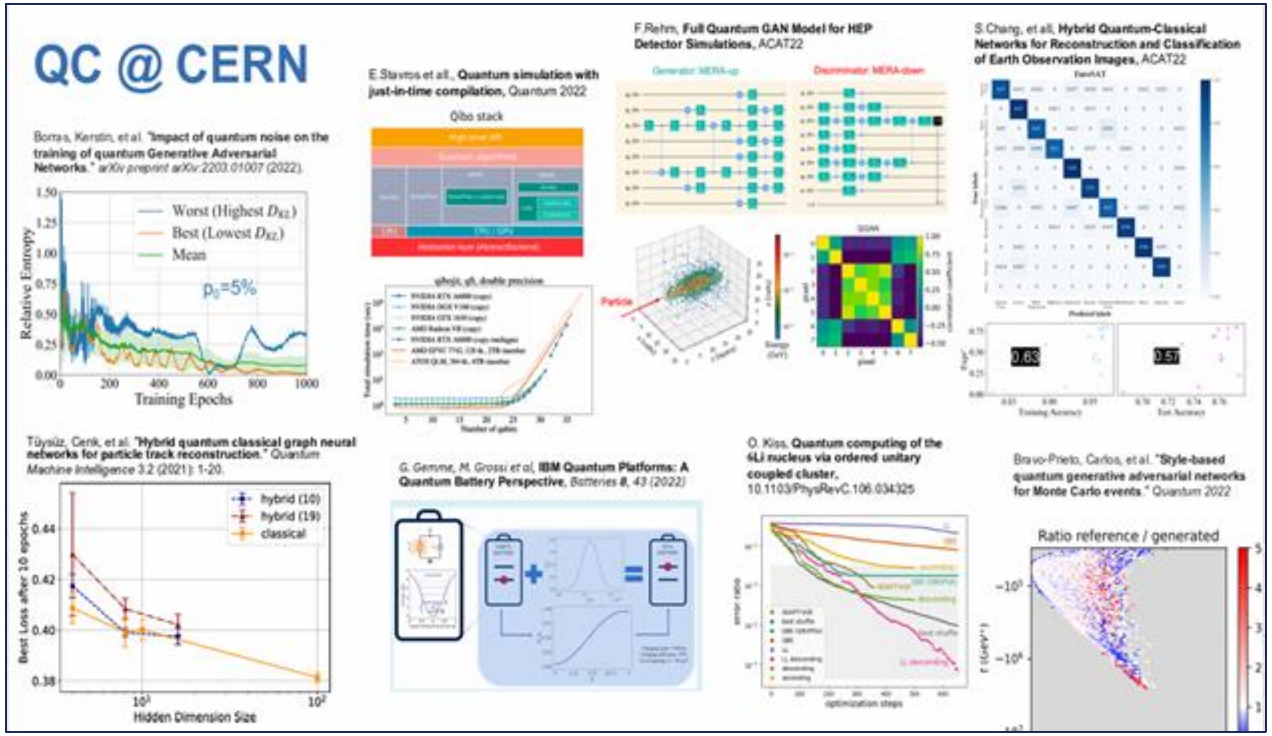
- Quantum Simulations
- Tensor Networks
- QML
  - Kernel based methods
  - Geometric Machine Learning
  - Generative Models
  - Supervised Learning (classification /regression tasks)

Methods and algorithms modelling:

- Noise studies
- QML trainability and generalization properties

Frameworks and Tools:

- QIBO
- QUASK



NEW! Machine Learning for hardware characterization and qubits systems readout

M. Casals, *U. P.Catalunya*
Poster

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Guided Graph Compression for Quantum Graph Neural Networks

Mikel Casals[1], Vasilis Belis[2], Michele Grossi[3], Elias F. Combarro[4], Eduard Alarcón[1] and Sofia Vallecorsa[3]
[1]Universitat Politècnica de Catalunya, [2]ETH Zurich, [3]European Organization for Nuclear Research (CERN), [4]University of Oviedo

Symmetry breaking in geometric quantum machine learning in the presence of noise

Cenk Tüysüz, Su Yeon Chang, Maria Demidik, Karl Jansen, Sofia Vallecorsa, Michele Grossi
@cenk_tuysuz
ctuysuz@mail.desy.de

PRX Quantum 5, 030314

C. Tuysuz, *DESY*
Monday afternoon

@

Guided Quantum Compression for high-dimensional data classification

Vasilis Belis (ETH Zurich)

Mach. Learn.: Sci. Technol. 5 035010 (2024)
Collaborators: P. Odagiu, M. Grossi, F. Reiter, G. Dissertori and S. Vallecorsa

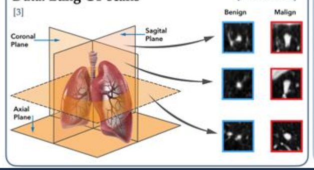
QTML 2024, 27 November 2024

V. Belis, *ETHZ*
Wednesday morning + Poster

Quantum-Inspired Tensor Networks for Unsupervised and Supervised Cancer Detection in Medical Imaging

Ema Puljak, M.A. González Ballester, A.Garcia Saez, M.Pierini, M. Grossi

Data: Lung CT scans [LIDC dataset] [3]



Quantum-Inspired: Motivation and Goals

- Leverage complex relationships ⟶ requires less data
- Matches classical methods even on smaller datasets and lower image resolution
- Robustness to new unseen diseases

	Unsupervised	*Supervised*
pros	no labels	labels
cons	lower bound of supervised	lack of labeled data

Challenges

- Embedding large medical images into **Tensor Networks**
- Limited number of labeled medical samples

E. Puljak, *CERN*
Poster

J.J. Martinez de Lejarza, *U. Valencia*
Poster

Quantum integration of decay rates in perturbation theory

Jorge J. Martínez de Lejarza*[a], David F. Rentería-Estrada[a], Michele Grossi[b] and Germán Rodrigo[a]
*jormard@ific.uv.es
[(a)]Instituto de Física Corpuscular, Universitat de València - Consejo Superior de Investigaciones Científicas, Parc Científic, E-46980 Paterna, Valencia, Spain
[(b)] European Organization for Nuclear Research (CERN), 1211 Geneva, Switzerland

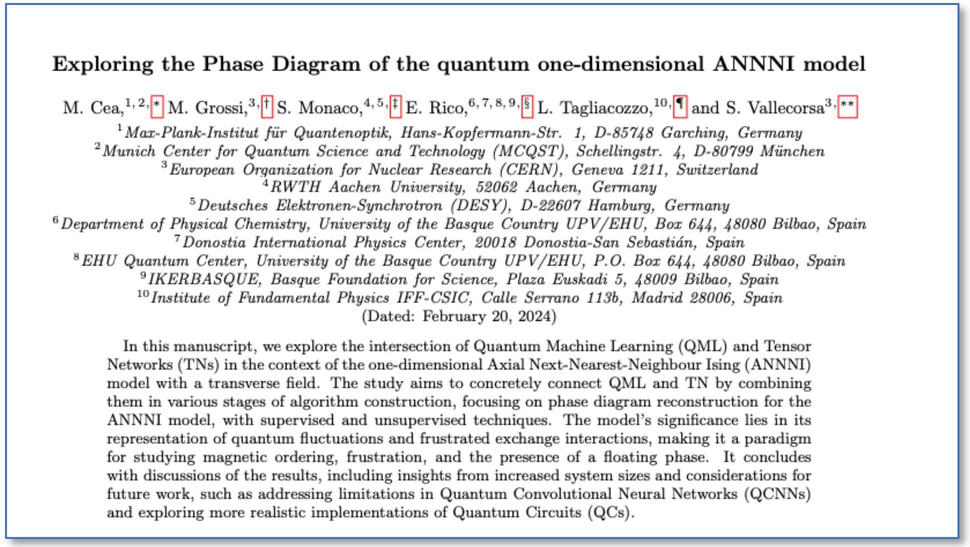
arXiv:2409.12236

QML for quantum data: drawing phase diagrams

Cea, at al. , arxiv (2024)

Monaco, at al. Physical Review B 107.8 (2023): L081105

- **Use MPS to study phase diagram of a Ising model**
  - State-of-the-art caracterization incl. Floating Phase
  - Provide input to QML algorithm
- **(Un-)Supervised QML to classify the ground state**
- **Bottleneck from access to classical training labels**
  - Train in integrable subregions
  - Use an Anomaly Detection approach



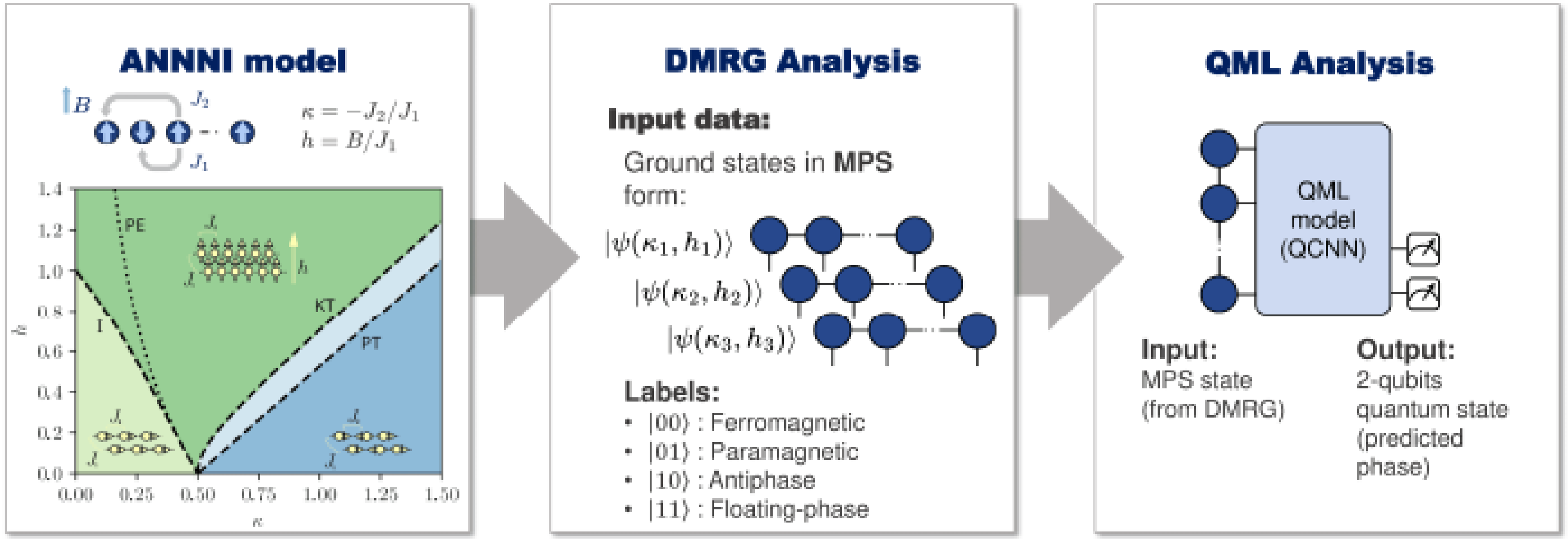
Exploring the Phase Diagram of the quantum one-dimensional ANNNI model

M. Cea,[1,2,*] M. Grossi,[3,†] S. Monaco,[4,5,‡] E. Rico,[6,7,8,9,§] L. Tagliacozzo,[10,¶] and S. Vallecorsa[3,**]

[1] *Max-Plank-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany*
[2] *Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München*
[3] *European Organization for Nuclear Research (CERN), Geneva 1211, Switzerland*
[4] *RWTH Aachen University, 52062 Aachen, Germany*
[5] *Deutsches Elektronen-Synchrotron (DESY), D-22607 Hamburg, Germany*
[6] *Department of Physical Chemistry, University of the Basque Country UPV/EHU, Box 644, 48080 Bilbao, Spain*
[7] *Donostia International Physics Center, 20018 Donostia-San Sebastián, Spain*
[8] *EHU Quantum Center, University of the Basque Country UPV/EHU, P.O. Box 644, 48080 Bilbao, Spain*
[9] *IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain*
[10] *Institute of Fundamental Physics IFF-CSIC, Calle Serrano 113b, Madrid 28006, Spain*

(Dated: February 20, 2024)

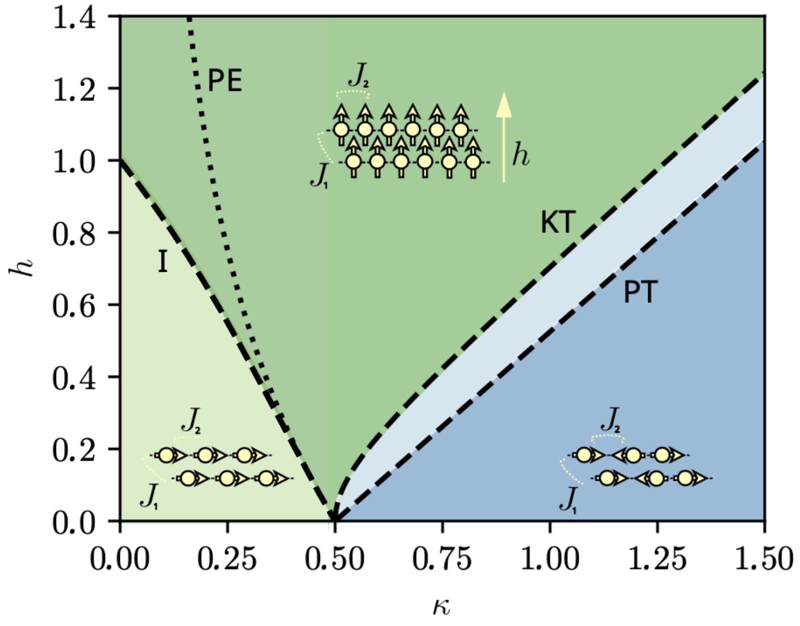
In this manuscript, we explore the intersection of Quantum Machine Learning (QML) and Tensor Networks (TNs) in the context of the one-dimensional Axial Next-Nearest-Neighbour Ising (ANNNI) model with a transverse field. The study aims to concretely connect QML and TN by combining them in various stages of algorithm construction, focusing on phase diagram reconstruction for the ANNNI model, with supervised and unsupervised techniques. The model's significance lies in its representation of quantum fluctuations and frustrated exchange interactions, making it a paradigm for studying magnetic ordering, frustration, and the presence of a floating phase. It concludes with discussions of the results, including insights from increased system sizes and considerations for future work, such as addressing limitations in Quantum Convolutional Neural Networks (QCNNs) and exploring more realistic implementations of Quantum Circuits (QCs).



The ANNNI phase diagram

$$H_{ANNNI} = -J_1 \sum_{i=1}^{N-1} \sigma_i^x \sigma_{i+1}^x - J_2 \sum_{i=1}^{N-2} \sigma_i^x \sigma_{i+2}^x - B \sum_{i=1}^{N} \sigma_i^z,$$

$$\kappa = -J_2/J_1 \text{ and } h = B/J_1$$

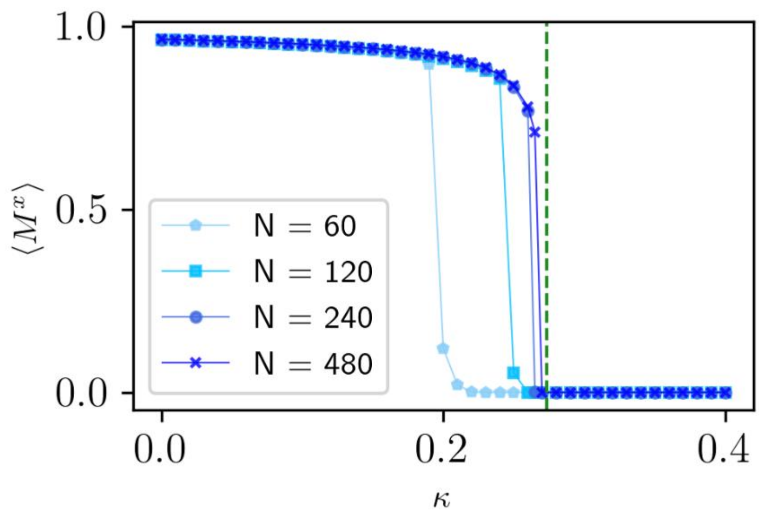


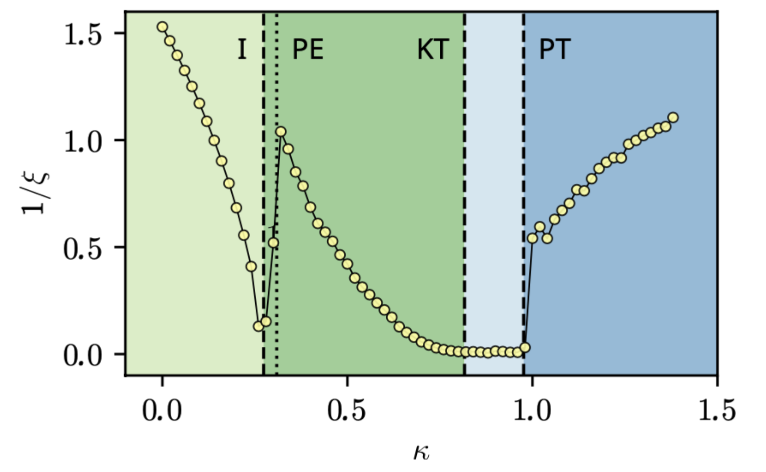
Use MPS representation of ANNNI model

- DMRG to analyse phase diagram of finite size systems (up to 480 sites)
- Detailed properties study

Study correlation range by fixing the transverse field and varying the frustration parameter:

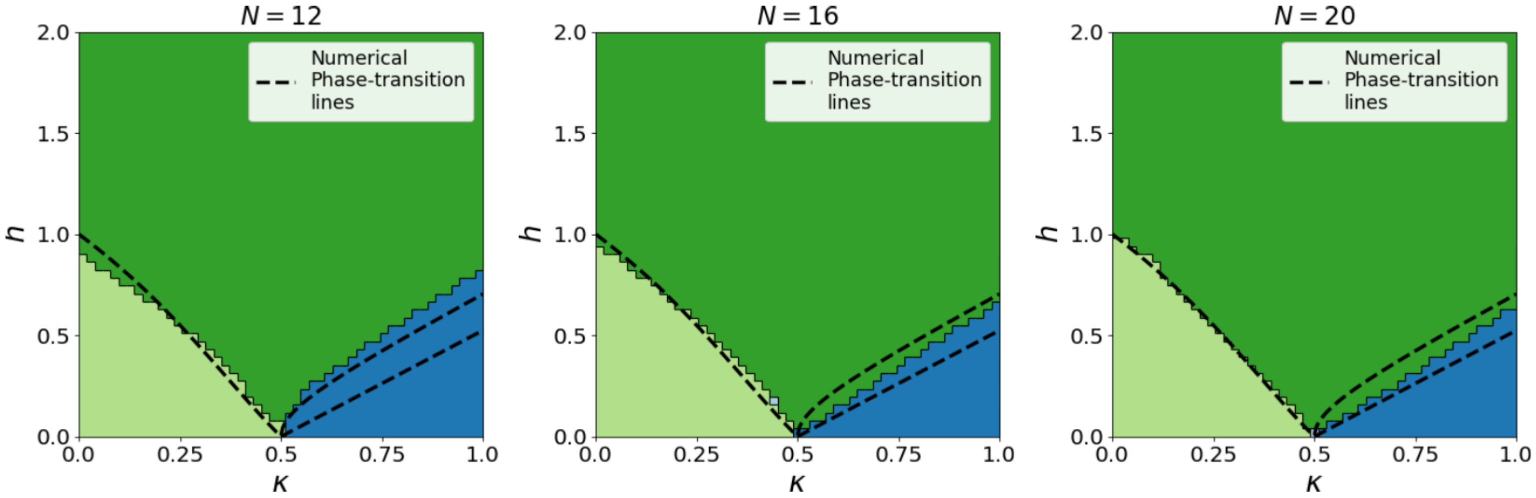
Generate wave function (up to 20 spins) as input to the QML analysis

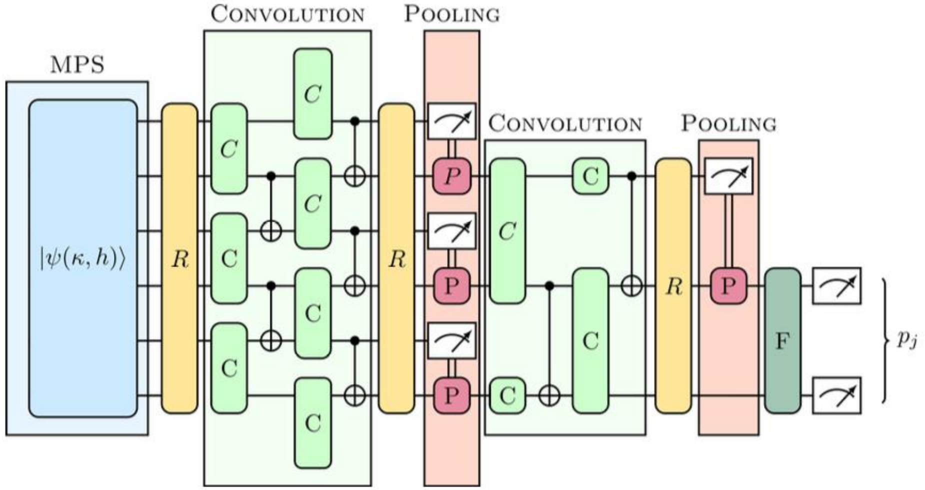




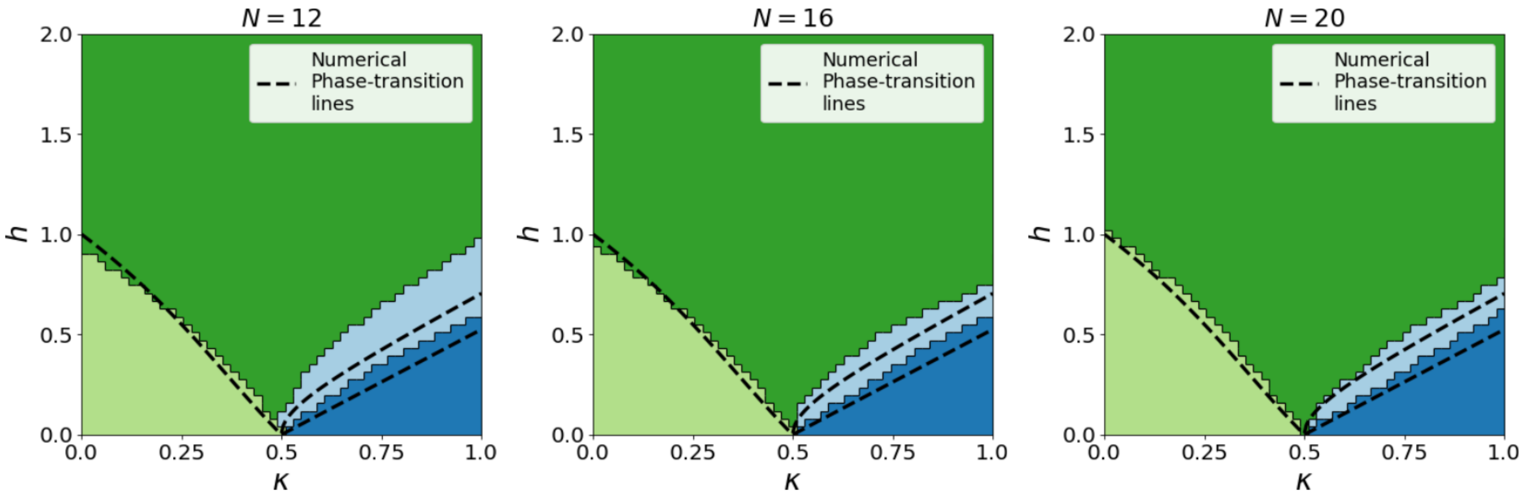
Supervised Quantum Convolutional NN

Train on analytically solvable points along the axes

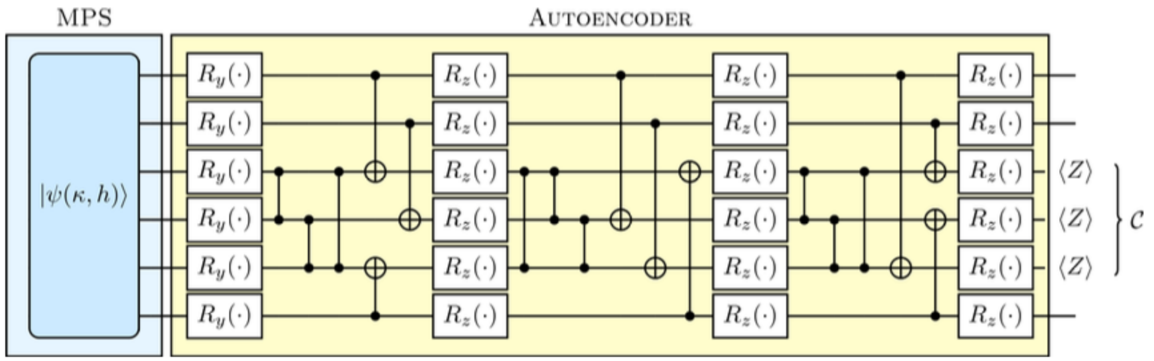


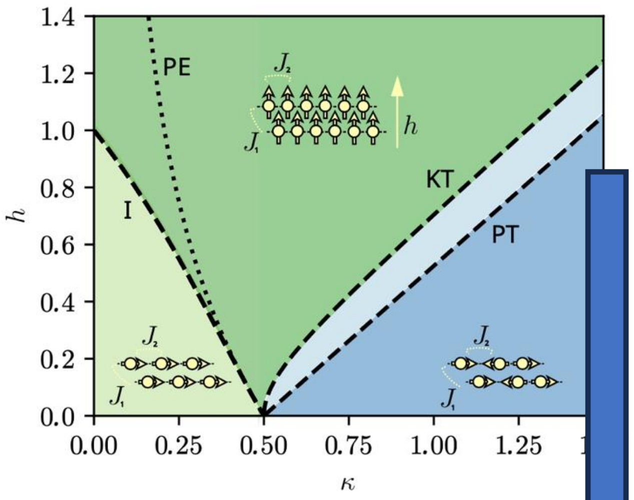


Train on all classes



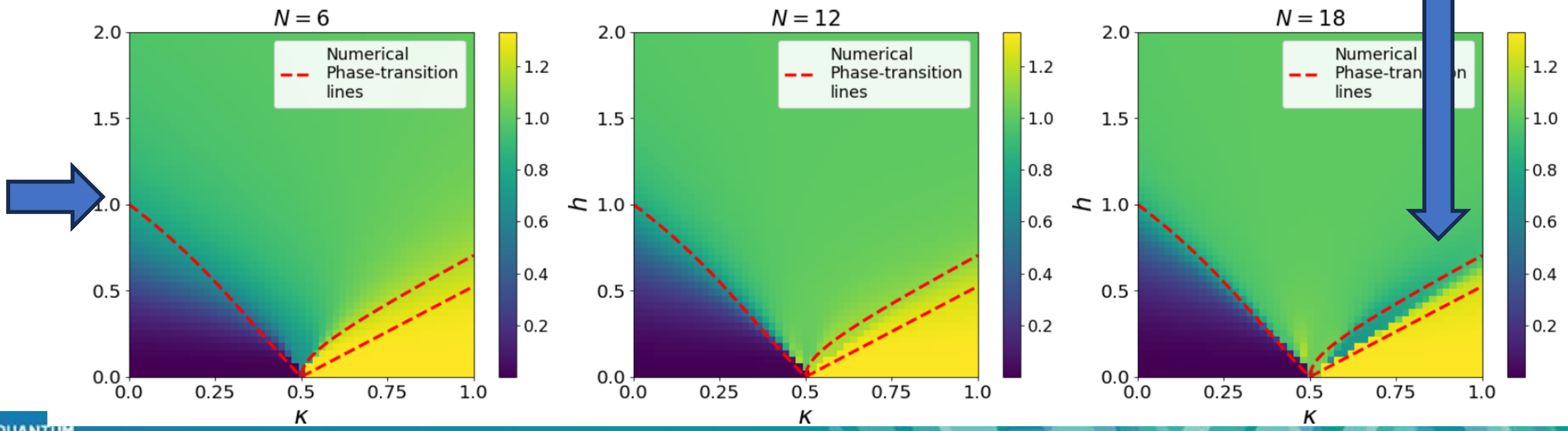
Unsupervised Quantum Auto-Encoder





Floating Phase !

Train on (0,0) state



Practical QML

Theoretical modelling and characterization of QML algorithms is key. However:

Heuristic approaches cannot be underestimated and
Applications in practical settings are essential for effective R&D

The CERN Quantum Technology research program takes this stance

- Focus on the applicability to High Energy Physics problems
- Flexible definition of advantage driven by HEP requirements

So what is the time scale for practical QML in HEP ?

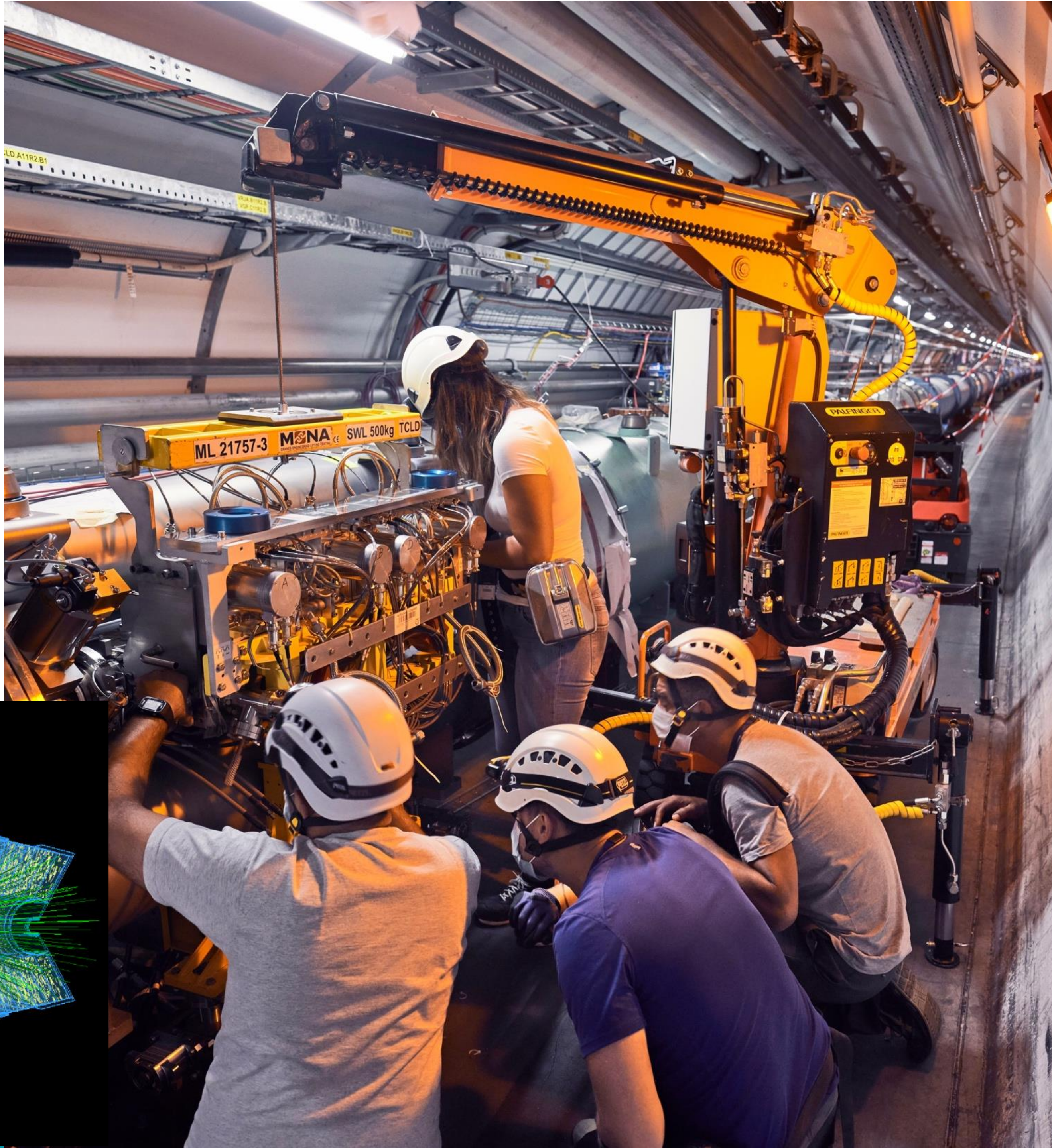
Future part 1:
High Luminosity LHC

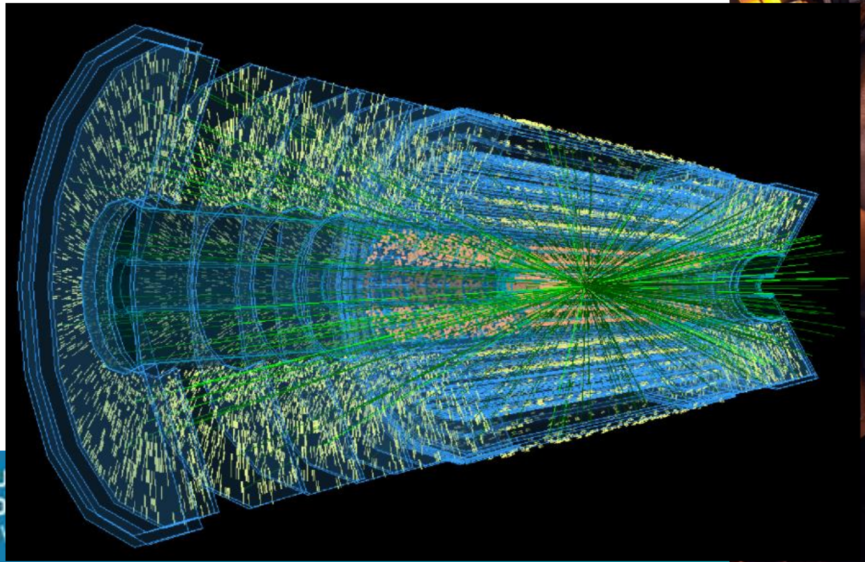
Start operation in 2030, and run until 2041

- Increase collision rate by factor 5-10

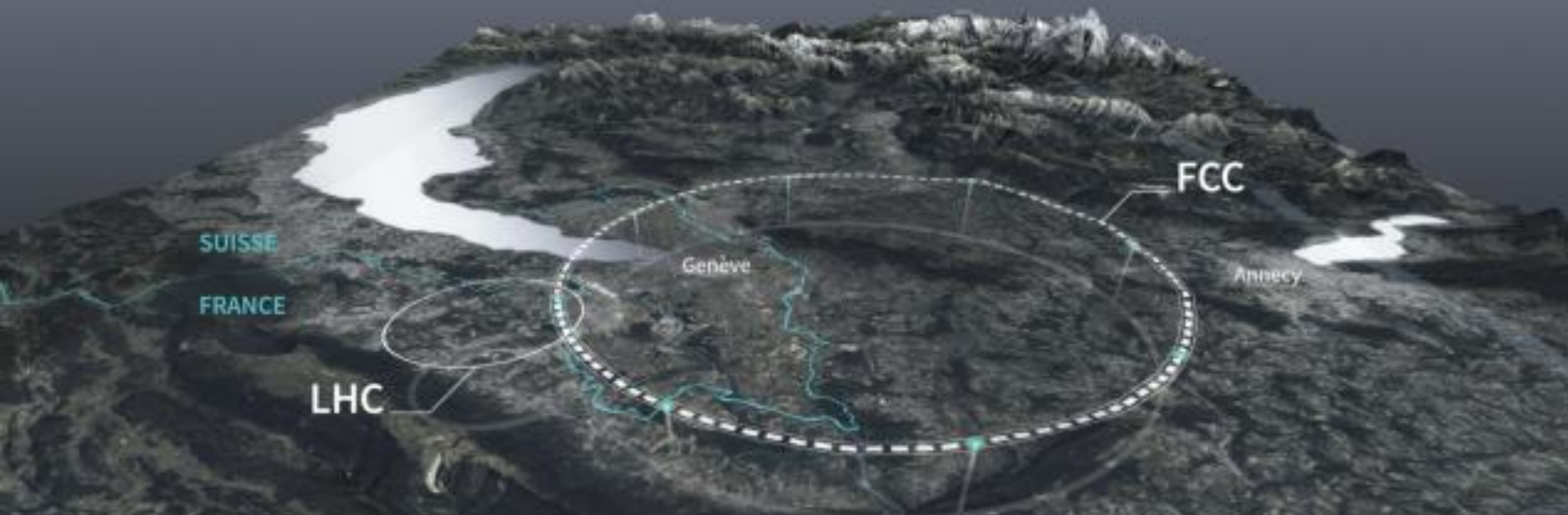
We can work toward QPU as accelerators in broader HPC context

- Hybrid algorithms (data compression)
- Demonstrators for medium size simulations





Future part 2: The Future Circular Collider (FCC)



- CERN is investigating the feasibility of a 91 km circumference collider
- Global collaboration: 150 institutes & 30 companies from 34 countries
- If approved, start of operation ≥ 2045 and continue until the end of this century

Time scale for fault tolerant quantum era ?

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CERN Main Auditorium

QUANTUM TECHNOLOGY CONFERENCE

QT4HEP

20-24 January 2025

Thank you!

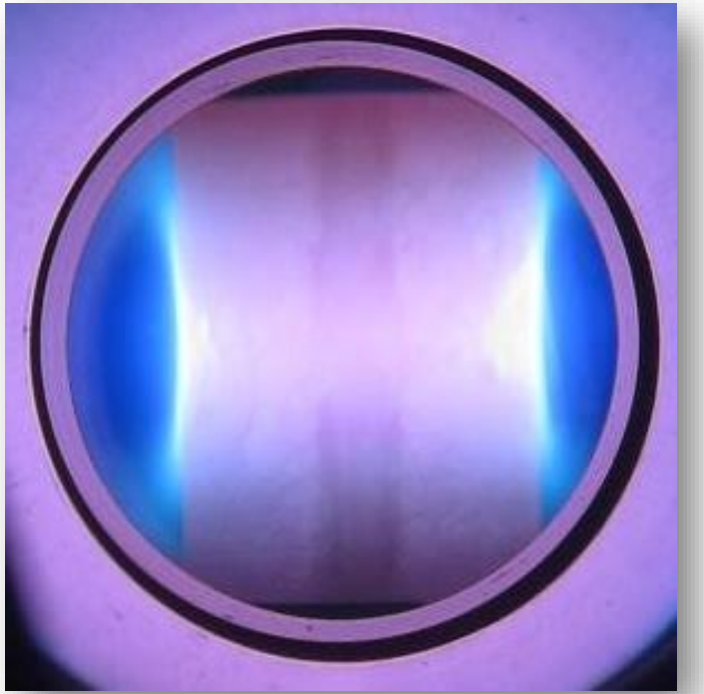
CERN

QUANTUM TECHNOLOGY INITIATIVE

Unique CERN expertise

Artificial Intelligence on FPGAs (based on CERN expertise on DAQ systems)

- Error correction is one of the greatest outstanding challenges in **quantum computing**. Any error correction has to happen sufficiently fast such that it is within the lifetime of the qubit. CERN's expertise in fast inference and machine learning could be a valuable contribution to this field.
- Improved error correction on quantum computer



Superconducting Coatings for RF Cavities

Unique expertise at CERN with potential impact for both quantum computing and quantum networking

- **Quantum Computing**
  Explore SRF Cavities for bosonic quantum computers
- **Quantum Networks**
  use of SRF Cavities for quantum transducers?

White Rabbit technology for time synchronisation

Initially meant for **large physics facilities**: CERN, GSI. . .

Based on **well-established standards**

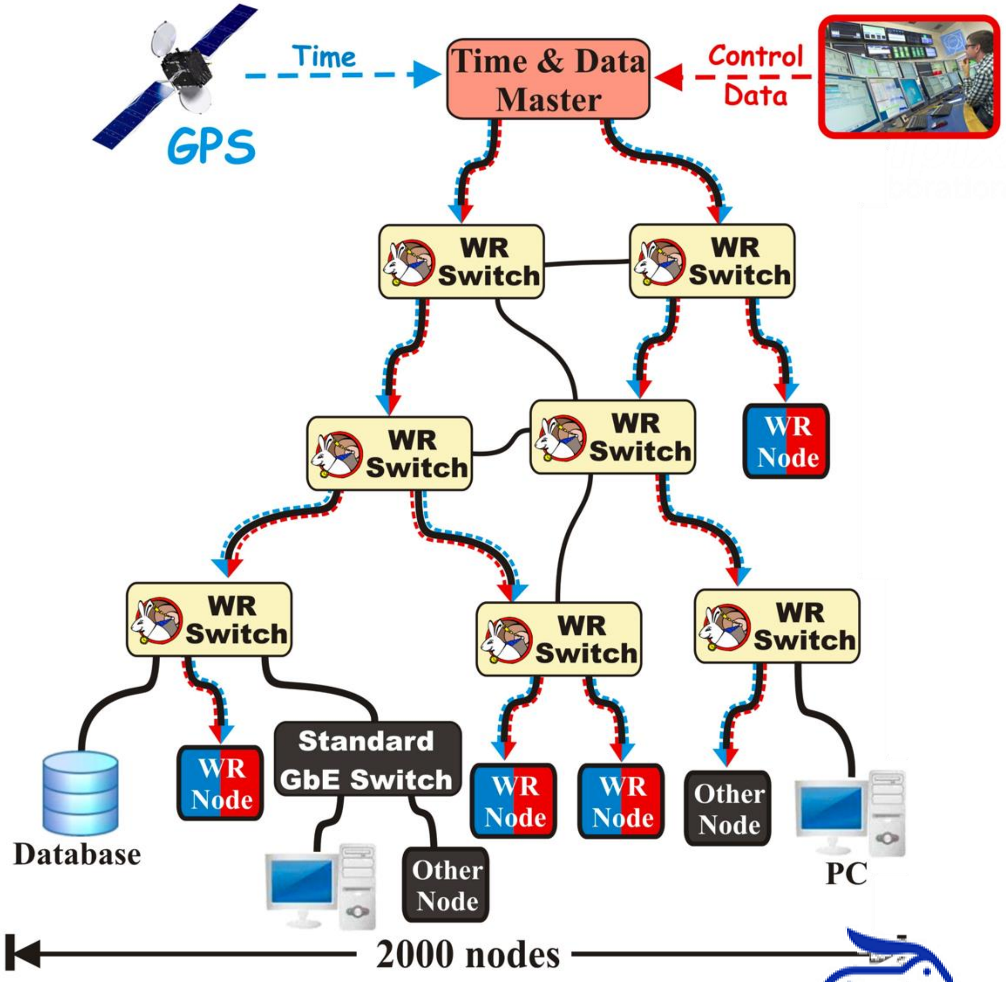
- Ethernet (IEEE 802.3), Bridged Local Area Network (IEEE 802.1Q), Precision Time Protocol (IEEE 1588)

Extends standards to meet new requirements and provides

- **Sub-ns synchronisation**
- **Deterministic data transfer**

Initial specs: links ≤10 km & ≤2000 nodes

Open Source and commercially available



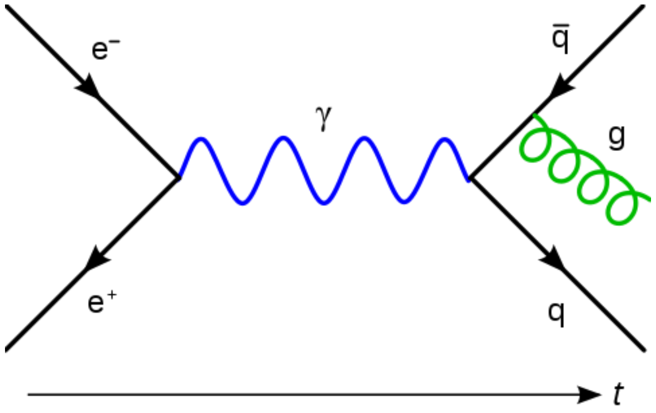
13th WR Workshop (21-22 March 2024 at CERN) https://ohwr.org/project/white-rabbit/wikis/mar2024meeting. and

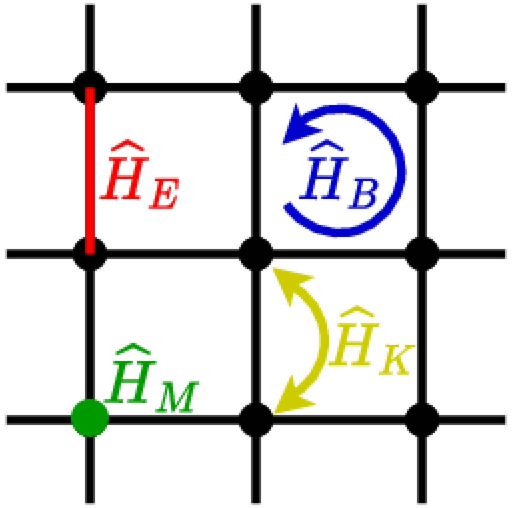
White Rabbit COLLABORATION

Example 1: Simulation of Real-Time Phenomena

Challenge

Theoretical predictions of scattering processes have limitations which make them applicable in regimes accessible via perturbation theory mainly capturing equilibrium properties (e.g. Monte Carlo methods). The “sign problem” and the complexity of numerical integration make real-time simulations challenging.





Chen, Zhuo et al. *ArXiv* abs/2212.06835 (2022)

Goals

Use the Hamiltonian formalism by discretising the space dimensions in square/cubic lattices and keeping time as a continuous variable.

Ex: Kogut-Susskind formulation of (2+1)D QED

$$H_{tot} = H_E + H_B + H_m + H_{kin}$$

Quantum methods

The Hamiltonian can be encoded on a quantum computer using various ansatz, the ground-state energy can be found using methods like VQE, SSVQE, or VQD

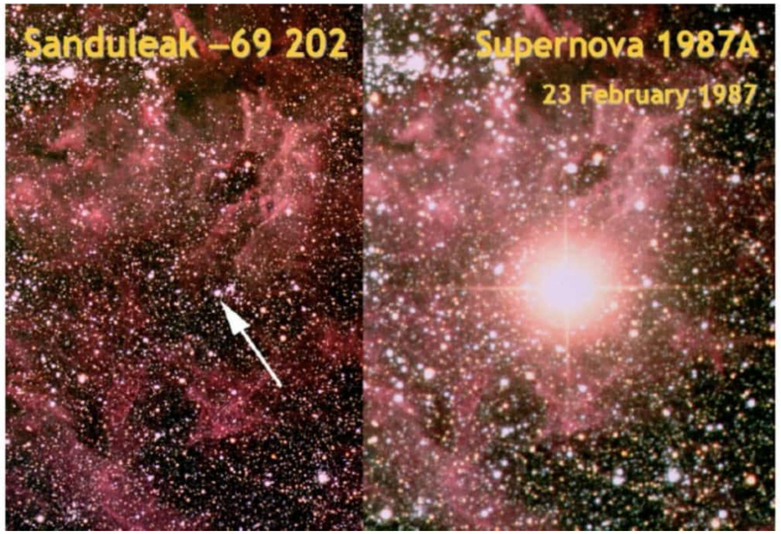
Analog quantum devices can also be used to approximate the time evolution of the target H.

Tensor Networks are interesting at equilibrium and out-of-equilibrium (for low entanglement production)

Example 2: Collective Neutrino Oscillations

Challenge

Neutrinos play a central role in extreme astrophysical events (supernovae or neutron star). Neutrino clouds are a strongly coupled many-body system, direct solution of the flavor evolution equations can be exponentially hard with classical simulations.



(Image: IIT Guwahati)

Goals

Study the flavor evolution of a homogeneous gas of neutrinos both at fixed density and at different local conditions (e.g. within the emitting neutron stars and as they travel in space) using a Hamiltonian formulation

$$H = \sum_{i=1}^{N} \boldsymbol{b_i} \cdot \boldsymbol{\sigma_i} + \lambda_e \sum_{i=1}^{N} \sigma_i^z + \frac{\mu}{2N} \sum_{i<j}^{N} \left(1 - \cos\theta_{1j}\right) \boldsymbol{\sigma_i} \cdot \boldsymbol{\sigma_j}$$

Quantum methods

The Hamiltonian can be encoded on a quantum computer using 1 qubit per neutrino, which so far restricts the simulation to small N numbers.

Evolution of the method involves scaling to higher N → more qubits, and more sophisticated initial conditions than simple wave-functions of non-correlated neutrinos.

Example 3: Particle Jets and Trajectory reconstruction

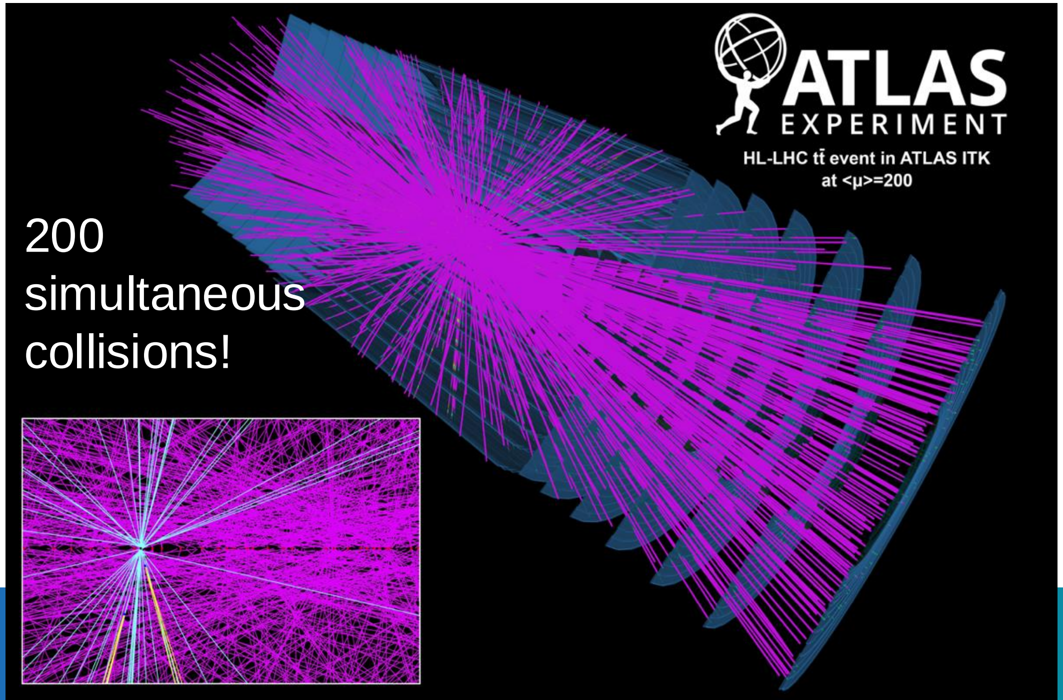
Challenge

Reconstruction of high-level physics features (ex. trajectories) from detector output is a complex task due to the high granularity geometry of detectors.

At next generation hadronic collider detectors, the dimensionality of the problem will increase by orders of magnitude.

Goals

Reduce time to solution. Pattern recognition tasks are formulated as multi-step processes. The goal is achieved by accelerating individual steps or designing new end-to-end approaches beyond today's estimation algorithms.



Quantum methods

The problem can be formulated as **QML,** as a **energy minimisation problem** (using both quantum annealers and digial computers) or as **a search problem (using quantum associative memories)** (ex. Quantum Associative Memory (annealer based **or** digital)