

# **Opinions Libres**

le blog d'Olivier Ezratty

# CERN QT4HEP, LHC, Atlas, CMS and antimatter factory

From January 20th to 23rd 2025, I participated in the **QT4HEP conference at CERN** and had a chance to visit several experiments from CERN. This was quite an experience that I recount here.

# This illustrated post contains:

- A description of **QT4HEP's conference highlights**.
- A primer on high-energy particle physics.
- An overview or CERN activities.
- A presentation of the **LHC** and its technology.
- A photography report of Atlas, CMS, and the antimatter factory.
- A small reminder that the **web and HTML** were created at CERN.



### **QT4HEP** conference

The Quantum Technologies for High-Energy Physics conference was the second one of the kind after the previous edition in 2022. It is organized by the CERN Quantum Technologies Initiative. CERN is also a cofounder of the Open Quantum Institute which deals with the societal impact of quantum technologies.

The QT4HEP conference goals was to showcase how HEP physicists can use quantum technologies in their

work and how HEP physics could potentially help develop new quantum technologies. It brought together highenergy particle physicists interested in quantum technologies (computing, sensing, communications), and specialists in the latter fields. I met there with many interesting people from various backgrounds, both from the academic world and from companies like Nu Quantum, Single Quantum, IDQ, Amazon, Pasqal, and others. You can download the talks presentations on the **event site**.

I was there for delivering a talk providing an overview of the state of the art of quantum computing software and hardware: Quantum computing roadmaps towards fault-tolerance (31 slides presentation and video recording). I was invited there by Benjamin Frisch and Amanda Diez Fernandez from CERN.

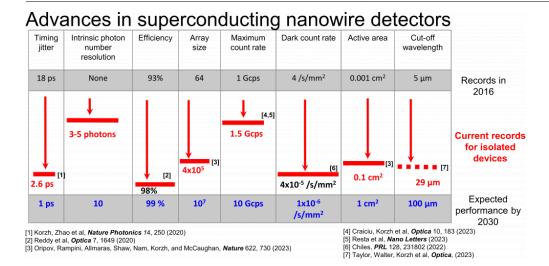


The conference was introduced by **Enrica Maria Porcari** (head of CERN IT) and **Sofia Vallecorsa** (head of CERN OTI).

It was followed by a first talk by **Petra Scudo**, a technology expert from the European Commission Joint Research Centre based in Italy, Belgium, Spain, the Netherlands and Germany, an in-house scientific and technical service of the EU that works for more than 30 policy departments. She spent most of her time describing EuroQCI programs in space and terrestrial quantum communications.

I will mention here a couple presentations from the conference. There were **many other** that I don't cover here, including those about various quantum algorithms to simulate high-energy physics phenomena and experiments and also, quantum sensors used in high-energy physics. You hear a lot about simulating lattice gauge theory and Schwinger models, being part of quantum fields, quantum electrodynamics and quantum chromodynamics domains. In my own presentation, I highlighted the fact that these quantum dynamics simulations are easier to implement, even in NISQ, than quantum chemistry simulations. It exemplifies the fact that quantum computing may become useful to physicists before it helps industries.

**Boris Alexander Korzh** from the University of Geneva **covered** high-speed SNSPD (single nanowire superconducting photon detectors) used for clock-rate scaling in quantum networks. It contained an interesting chart showing the progress in 9 years and expected advances till 2030. Particularly, the increase in maximum count rate will lead to grow the clock-rate in quantum communications to over 10 GHz as well a PNRD (photon number resolution detectors) with 12.5 GHz clock rates, useful in quantum computing.



**Felix Bussière**, VP R&D from IDQ (Switzerland), also **talked** about PNR SNSPDs (photo number resolution single nanowire superconducting photon detectors...), mentioning Gaussian boson sampling and Quandela experiments as well as their work with Orca Computing.

**Arian Stolk** from QuTech, Delft, did two presentations, **one** on entanglement between QPUs, including one experiment using NV centers based QPUs and the **other one**, with a broad overview on the quantum Internet.

**Simone Eizagirre Barker,** product manager at Nu Quantum (UK) **presented** their QPU's photonic-based interconnect technology, the UKRI sponsored LYRA project for the creation of a prototype of a data-centre compatible rack-mounted Quantum Networking Unit (QNU), their relation with the **White Rabbit** sensors interconnect project and some insights on how to distribute logical qubits across multiple QPUs.

**Mael Flament**, Qunnect's CTO (Brooklyn, NYC, USA) described his room temperature quantum memory that can be used to create long distance entanglement sharing quantum networks.

**Mateus Sena** from Deutsche Telekom's T Labs **described** their various quantum communications projects. They work noticeably with Qunnect and VeriQloud.

**Marianne Schoerling** presented the Open Quantum Initiative, which is funded by UBS and is willing to avoid the misuse of quantum technology.

**Fabio Maltoni** from the Universities of Bologna and Louvain **presented** the kinds of quantum physics observables used in high-energy physics, focusing on the top quark, the heaviest elementary particle from the standard model, neutrons and protons being made of "up" and "down" quarks. It is not found in common matter made of baryons given its lifetime observed at the LHC is of only 10?2? second. I liked the laundry list of fundamental questions asked by Fabio Maltoni in his presentation (below). He also dealt with Bell entanglement tests done with the LHC using both Atlas and CMS experiments! I discovered the notion of **toponium**, a composite low-lifespan top/down quark particle, which I won't detail here.

- \* Is there a relation between symmetries and entanglement? 1812.03138, 2210.12085
- \* What is the best frame for making quantum measurements? 2311.09166
- \* How is decoherence happening for collider final states? What about NLO?
- \* When is the actual measurement of spin really happening? 2401.06854
- \* Is there an optimal way to do quantum tomography? 2311.09166
- \* Is there a general approach to quantum measurements at colliders? 2201.03159
- \* Are there quantities in colliders that can be entangled beyond spin and flavour? Color?
- \* Is the information entropy a useful quantity in collider physics?
- \* Are SM interactions minimal in with respect to alternative theories? 2307.08112
- \* Can multi-partite systems be studied at colliders? 2310.01477
- \* Is entanglement conserved/augmented/lost in SM interactions? 1703.02989,2209.01405
- \* Is there a relation between scattering in QFT and computing in IS? 2312.02242, 2310.10838
- \* Can entanglement be used to do model building? 2307.08112
- \* What is the analogue of purification at collider processes?
- \* Can we test Bell-inequalities on an event by event basis?
- \* What is the analogue of distillation? 2401.06854
- \* What is the most general constraint on non-locality from scattering processes? 2401.01162
- \* Entanglement in neutrino oscillations? Many papers, see 2305.06095
- \* Entanglement and Bell in B0/B0-mixing? Several papers, see 2106.07399
- How should we think about virtual particles? 2211.05782
- Maximal or minimal entanglement as a guiding principle? 1703.02989 vs 2307.08112 and 2410.23343

**Francesco de Dominicis** from INFN (Italy) **presented** a superconducting gamma ray detector. That's quite an uncommon quantum sensor.

**Ankul Prajapati** from LKB (France) **presented** advances in circular Rydberg cold atom experiments.

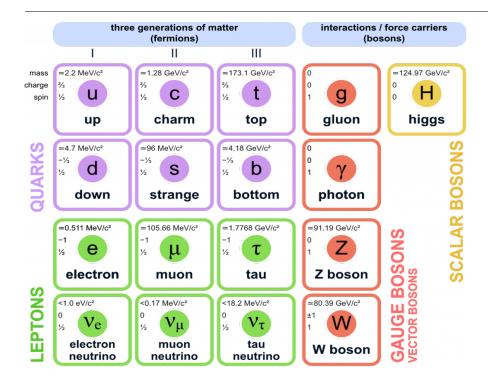
**Young Jin Kim** from Los Alamos National Laboratory (USA) **presented** his work on axions detection using optical detection and spin squeezing. This is related to the search of dark matter.

**Denis Lacroix** from ijcLab (France) **presented** recent progress in the description of atomic nuclei using quantum computers and quantum phase estimation (QPE). He teams up with various researchers, including Thomas Ayral from Eviden.



# **HEP** primer

High-energy particle physics is about learning the most inner components of matter (elementary fermions) and force carriers (elementary bosons) from the standard model, down to quarks and other elementary particles and fields (map below, from Wikipedia).



Unless you are a high-energy particle physicist, you may not know well all these particles. Neither do I! So, here is a primer on this that you can easily skip to read the remainder of this post:

- Quarks (purple) come in six "flavors" (up, down, charm, strange, top, bottom). They participate in the strong nuclear interaction, that is mediated by gluons force carriers. It is modeled by quantum chromodynamics (QCD). Quarks also carry fractional electric charges (+2/3 or -1/3 in units of the electron charge) and are always confined within composite particles called hadrons, including protons and neutrons. Neutrons and protons contain only up and down quarks, held together by gluon forces. The heavier charm, strange, bottom, and top quarks do not persist in matter. They rapidly decay into lighter up and down quarks. They appear in short-lived particles produced in high-energy experiments. In that bestiary, hadrons are particles bound by the strong interaction, while baryons is a subclass of hadrons composed of three "valence" quarks which determine their overall quantum numbers (electric charge, baryon number, and strangeness). And on, and on, and on, and on...!
- **Leptons** (green) are massive elementary particles which do not feel the strong interaction. They include the electron, muon, and tau, along with their corresponding neutrinos. Charged leptons (electron, muon, tau) can interact electromagnetically, while the related neutrinos engage only through the weak force and gravity. Unlike quarks, leptons appear as free particles in nature and have integer electric charges (electron, muon, tau each with -1, neutrinos being neutral with a 0 charge).
- Interactions and force carriers (red and yellow) contain the gauge bosons (photons, gluons, Z and W bosons) and the Higgs boson. These are mediating the interactions among quarks and leptons. Photons are massless bosons described quantum electrodynamics (QED). They do not carry electric charge and travel at the speed of light in vacuum. They participate to the exchange of energy with electrons, famously described in quantum physics in the Bohr atomic model. The strong force holds quarks together inside neutrons and protons. It is conveyed by eight types of gluons which are also massless. But gluons experience the interaction they mediate, creating gluon self-interactions. The weak interaction involves the exchange of the charged W bosons (W? and W?) and the electrically neutral Z boson, all of which are massive. The weak force acts over extremely short ranges, driving atomic nuclei beta decay (fission) and nuclear fusion. In this framework, the Higgs boson is the "quantum excitation of the Higgs field", a scalar field that

"spontaneously breaks the electroweak symmetry in the Standard Model". This mechanism explains how particles acquire mass.

Quarks and leptons are fermions massive particles. Quarks and leptons have their antiparticles, not shown in the typical standard model table as above, like antiquarks and antileptons, the most famous being the positron, which is the antiparticle of the electron. It was theoretically discovered by Paul Dirac in 1928. Even non charge particles like neutrinos have their antiparticles with a similar 1/2 spin but with different other quantum properties (opposite-signed lepton number and weak isospin (I skip the details here), and right-handed instead of left-handed chirality).

In quantum physics, fermions and bosons can also relate to composite particles made of elementary particles from the standard model. Depending on their total spin, easily computed with the number of neutrons being odd or even, an atom can be a boson or a fermion, following the famous Einstein-Bose or Fermi-Dirac statistics. In plain words, bosons with the same quantum numbers can stick together while fermions can't, following Pauli's exclusion principle.

One key question I have in mind here is "how classical quantum physics is different from high-energy particle physics"? Here is a simple answer...

Quantum physics used in so-called quantum technologies deals with atoms, molecules, electrons and photons, and involves (relatively) low-energy phenomena. It explains the exchange of energy between light and matter, atomic spectra, chemical bonding, and the properties of materials. It is essential in condensed matter physics (superconductors), quantum chemistry, and nanotechnology involving all semiconductors. It mostly use non-relativistic effects although the Dirac relativistic equation helps explain some atomic spectra artefacts. In classical quantum physics, only photons are created and annihilated. The theoretical framework is based on a set of postulates including the representation of states by wavefunctions (Schrodinger's wave equation), the manipulation of Hilbert spaces, observables by matrix operators in such spaces, and the probabilistic interpretation of measurement outcomes. They are derived with concepts such as superposition and entanglement within a fixed particle number framework.

High-energy physics focuses on the fundamental constituents of matter and their interactions at the highest energies and smallest scales, below neutrons and protons for example. It explores particles like quarks, leptons, bosons, and the forces that govern their interactions. It involves massive particles creation and annihilation. It helps understand the fundamental forces of nature, the Standard Model of particle physics, and the phenomena occurring in particle accelerators and cosmic events. It also explore physics beyond the Standard Model, such as with supersymmetry or string theories. The main theoretical frameworks are the relativistic quantum field theory, quantum chromodynamics, gauge symmetry, renormalization techniques, and spontaneous symmetry breaking giving rise to particle masses creation. Elementary particles also have additional quantum numbers (properties) like isospin (for quarks and particles made of quarks like protons and neutrons), and weak isospin, charm (for so-called left-handed fermions and also some bosons), strangeness (which relates to the number of strange quarks and antiquarks in composite particles), topness (difference between the number of top quarks and top antiquarks in composite particles), bottomness (same for bottom quarks/antiquarks), baryon (1/3 the difference between quarks and antiquarks) and lepton numbers (difference between number of leptons and antileptons).

The second quantization formalism is a bridge between these two domains. It is widely used in non-HEP quantum physics and technologies. It involves the use of creation and annihilation operators, which enable the addition or removal of particles from quantum states. It makes use of number operators counting the number of particles like photons in a given state (aka Fock states). The second quantization is heavily used in condensed

matter physics, including the study of complex materials like superconductors and superconducting qubits, quantum phase transitions, and also quantum photonics.

#### More on this:

- The Standard Model of Particle Physics by N. Besson, ISAPP school, March 2022 (66 slides).
- Higgs Boson, for dummies.
- Quantum Field Theory and the Standard Mode by Matthew D. Schwartz, Harvard, (870 pages) for HEP scientists.

#### **CERN** quick overview

CERN (Centre Européen de Recherche Nucléaire) is an international research organization created in 1954. It celebrated its 70 years of existence in 2024.



Is is focused on high-energy particle physics. One of CERN's missions is to search for the origins of the Universe. Its LHC is the greatest physics experiment on Earth, larger in size (but not costs, \$7.5B) than the international ITER nuclear fusion plan under construction in France (>\$25B), the US LIGO (\$1B) and the EU VIRGO gravitational waves detectors, the SOLEIL electrons synchrotron in France or the giant <u>Five-hundred-meter Aperture Spherical Telescope</u> (FAST) in China. Of course, these installations are used for different purposes, but all are related to physics or astrophysics.

CERN members are UE countries (Germany, Austria, Belgium, Bulgaria, Denmark, Spain, Finland, France, Greece, Hungary, Italy, the Netherlands, Poland, Portugal, Slovakia, Czechia, Sweden) and non-EU countries (Israel, Norway, United Kingdom, Switzerland). Its funding was of 1.37B€ in 2023 according to their 2023 report. The funding is proportional to its members GDP. CERN experiments installation are used, mostly remotely, by 12,370 users located in 80 countries, including the USA with its 2,007 users. CERN has 2,600 employees.

CERN uses a peak electrical power of 200 MW when the LHC is operating, mostly due to cooling it with liquid helium. Maintenance is done during winter for a simple reason: that is when the surrounding area, including Geneva, needs the most electricity, for heating. Likewise, in the USA, similar facilities are in maintenance during summer, when electricity is needed for air conditioning.

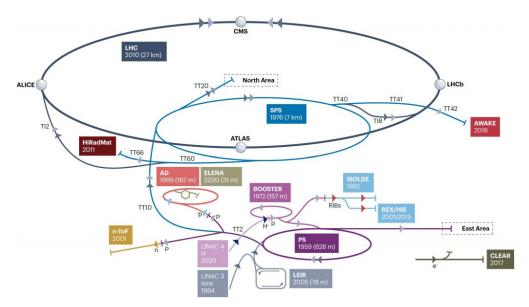
#### More on CERN:

- CERN history The historical milestones in 60 years of science, CERN, 2014.
- A timeline of CERN history by CERN, 2024.

• A history of CERN in seven physics milestones by Federica Riti et al, CERN, Nature Review Physics, 2024 (5 pages).

#### **LHC**

The Large Hadron Collider (LHC) is at the core of CERN's infrastructure. It is a protons and ions accelerator used by some underground experiments like Atlas and CMS. It is fed by a series of smaller synchrotrons built over several decades (BOOSTER, PS, SPS).



It is currently the world's largest and highest-energy particle accelerator, driving propulsing protons or ions at an energy level of 7 TeV. These are charged and massive particles. They are accelerated by an electric field and oriented by a magnetic field.

The 27 km tunnel hosting the LHC was actually built between 1985 and 1989 for the LEP, an electron-positron accelerator. It is between 50 and 175 m deep under the ground. The interior of the tunnel was replaced by the LHC infrastructure between 1998 and 2008, on top of the buildout of several large experiments along the way, like Atlas, CMS, ALICE and LHCb. It operated first in 2010 and the Higgs boson existence was discovered in the Atlas and CMS experiments in 2011 and reported in 2012. The LHC was then shut down and upgraded to increase its power (2013-2015) and for maintenance and other upgrades (2018-2022). The LHC is not perfectly circular but made of several straight and curved segments, magnetic fields being used to orient the proton/ions beams.

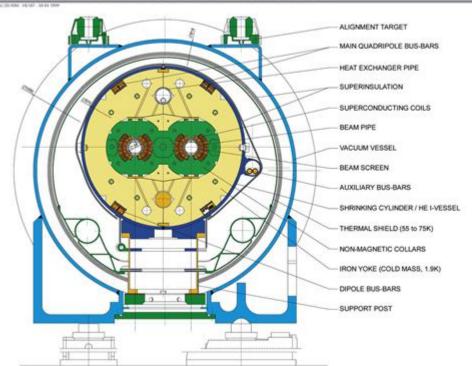
The two largest "experiments" are Atlas and CMS. They are also underground sitting in giant concrete caves. Both experiment project protons against each other in an opposite way, accelerated to a speed very close light speed (c). CMS is smaller than Atlas but heavier (see table below).

	Weight	Length	Height (m)
	(tons)	(m)	
ATLAS	7,000	42	22
CMS	12,500	21	15

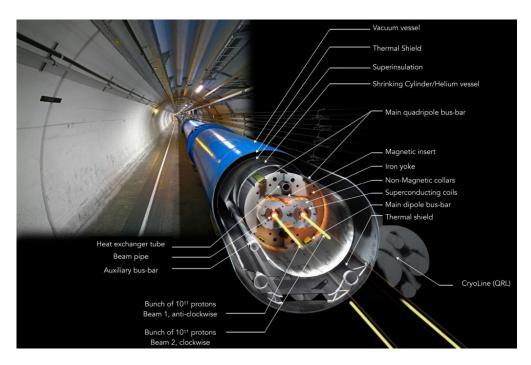
In the LHC, accelerated protons and ions travel inside two parallel, stainless-steel vacuum tubes known as "beam pipes", with an inside pressure of 10?¹? mbar, aka "ultra-high vacuum". As a comparison, the pressure in cold atom chambers used in neutral atoms quantum computers is slightly lower, at 1.3×10?¹¹ mbar, but in a

much smaller volume. These internal pipes have an inner diameter of 56 mm and drive the protons/ions in opposite directions. They are surrounded by a superconducting magnet operating at 1.9 K and cooled by a stream of liquid helium. The whole system is in a pipe aka "vacuum vessel" about 90 cm wide. The pipes send their particle beams on a given location in the Atlas, CMS and other experiments, their opposite direction creates a shock at an energy of 14 TeV per proton. It creates particles sent in all directions which are then detected by many sensors capturing their direction, velocity and energy. The proton beams are made of 2,808 bunches, each bunch containing 10<sup>11</sup>protons (100 billion), but the chance that opposite directions protons collide is very small. Still, the LHC can generate about 600 million particle collisions per second.





The LHC tunnel is about 3.8 m wide.



And the related energies and proton speeds generated in the various accelerators at CERN.

Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c<sup>2</sup>

Starting in 2025 or later, the LHC will run through a major upgrade, as part of the High-Luminosity LHC (HL-LHC) project. It will enable extend LHC operations until the early 2040s.

A future circular collider of 90.7 km circumference is being planned. The tunnel would first host the FCC-ee, an electron–positron collider. The FCC-hh would then be installed in the same tunnel, reusing the existing infrastructure, exactly like when the LHC experiment replaced the LEP experiment in the same 27 km tunnel. The FCC-hh will create collision energies of 100 TeV, vs the 14 TeV of the LHC. If funded (> 15B€), this project construction would start in 2030 with the FCC-ee starting operations in the mid 2040s and the FCC-hh starting around 2070. These time scales seem much longer than for the advent of some useful quantum computers!

For more documentation on the LHC:

- LHC The Guide, CERN (64 pages).
- 70?years at the high-energy frontier with the CERN accelerator complex by Oliver Brüning, Max Klein, Stephen Myers, Lucio Rossi, Nature Reviews Physics, September 2024 (10 pages).
- The Large Hadron Collider (LHC) and College Physics, (101 slides).
- Physics at Hadron Colliders by Beate Heinemann, 2010 (45 slides).
- Introduction to the Large Hadron Collider (LHC) to study the elementary particles by Gurpreet Singh Chahal, 2019 (35 slides).
- Cryogenics for particle particle accelerators accelerators by Ph. Lebrun, 2009 (78 slides).

## Atlas

At CERN, you visit the Atlas experiment with getting into a warehouse style building (below). It has some security doors and then a large elevator. After walking through various corridors and sas, you enter the big Atlas cathedral experiment. It is massive, way beyond anything you can discover when visiting a quantum experiment lab or any quantum technology facility.

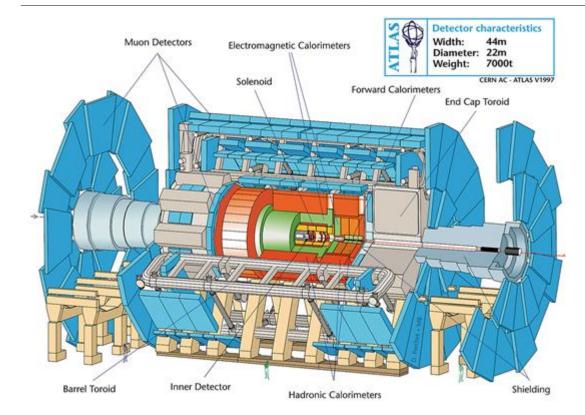
The proton-proton collisions occurring at the center of the Atlas (and CMS) experiments generate particles that decay in complex ways into even more particles that are themselves detectable.



Atlas contains four kinds of detectors zones:

- The **tracking chambers** which measure the trajectories of charged particles such as electrons, muons, and charged hadrons by recording their passage through large silicon pixel sensors, silicon microstrip layers, and a transition radiation tracker. From these precise trajectories, scientists can infer particles *momentum* by measuring trajectory curvature in the magnetic field.
- The **electromagnetic calorimeter**, which is liquid-argon based in Atlas, absorbs and measures the energy of electrons and photons through their electromagnetic showers, enabling accurate reconstruction of their *energy* and *direction*.
- The **hadronic calorimeter** using scintillating tiles and additional liquid-argon sections stops and measures the *energy* of strongly interacting particles like pions and protons. These hadrons produce extended hadronic showers that deposit their energy in deeper layers of the calorimeter.
- The **muon chambers** are the outermost layers of Atlas that detect muons after they penetrate the inner detector and calorimeters, and are measuring *momentum* under a dedicated toroidal magnetic field.

The data extracted from all these detectors is combined to identify and reconstruct the different particle types produced in the proton-proton collisions. Undetectable particles like neutrinos are inferred from missing transverse momentum.



Here is the view of the Muon detector (below). It is the only detector you can see when visiting Atlas.



So what is the Higgs boson and how is it detected in Atlas and CMS? To make things short, the Higgs boson is an excitation of the Higgs field, a scalar quantum field responsible for the creation of certain massive elementary particles in the Standard Model of particle physics. It explains how the universe created mass!

In the LHC, the proton-proton collision is generating these Higgs boson which then decay into electrons, muons and photons through two main paths:

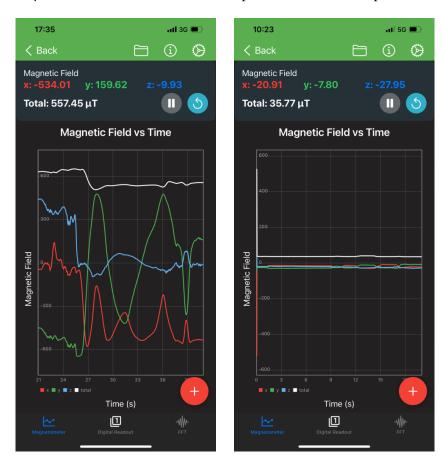
H? ZZ(?)? 4?, ? corresponding to an electron or a muon and Z and Z(\*) to Z bosons.

H???, two photons.

One very surprising discovery when visiting the Atlas and CMS experiments is that, although we were about

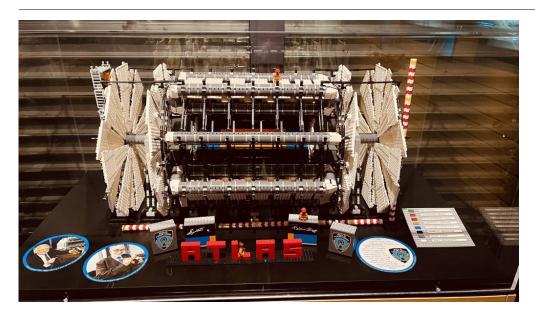
100 m underground, our smartphones were connected to 3G, 4G and 5G depending on the location, thanks to a contract with Swisscom.

When I was visiting Atlas, I measured the ambient magnetic field with my smartphone using the **Physics Toolbox** application. It detected a field of about 500  $\mu$ T while outside Atlas, the magnetic field was about 20 to 30  $\mu$ T. It is not hazardous at all. In hospitals, MRI scanners operate at field strengths of 1.5 T to 3 T!



# More on this here:

- The ATLAS experiment at the CERN Large Hadron Collider, 2008 (439 pages).
- Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC by The ATLAS Collaboration, arXiv, July-August 2012 (38 pages).
- Students at Kopernikus-Gymnasium build ATLAS model, October 2023 (pictured below).



#### **CMS**

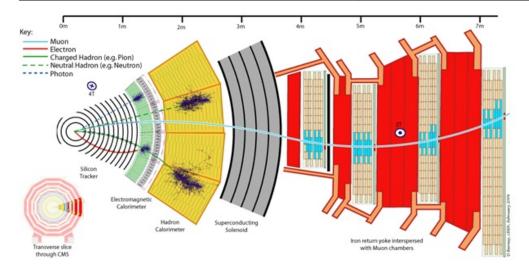
The CMS visit is a bit more impressive than with Atlas. First, you enter a big hall where the experiment was built. A large shaft was used to convey each large part down below at about 100 m deep. You also take an elevator which is in another shaft, again several corridors, and voilà, you are in CMS.

CMS is built around the following detectors:

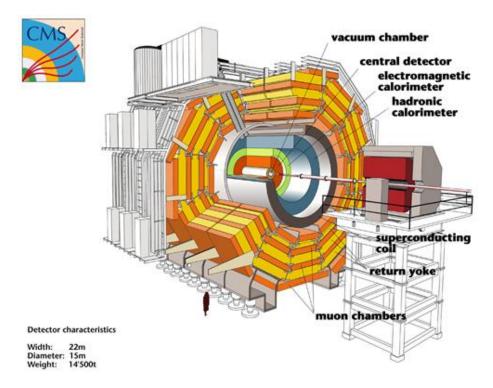
- A silicon pixel and strip tracker. It contains silicon sensors which are quite large compared to the sensors in digital cameras (measured in meters). They measure the trajectories of charged particles by recording their paths as they pass through multiple silicon layers. The tracker then reconstructs particles momentum and charge by observing their curvature in the strong magnetic field inside the CMS detector.
- An **electromagnetic calorimeter** (ECAL) made of lead tungstate crystal. It measures the energy and direction of electrons and photons. Interacting with the dense lead tungstate crystal, they create electromagnetic showers, which release energy.
- A scintillator hadron calorimeter (HCAL) made of brass. It detects and measure the energy of strongly
  interacting particles, such as pions and protons. These particles create "hadronic showers" when they
  interact with the brass absorber material. The resulting light from the scintillator layers is collected to
  measure their energy.
- Several **muon detection chambers** in the outermost layers of the CMS experiment. They detect muons paths in the magnetic field. Muons are heavier counterparts of the electron that penetrate through the inner detectors and calorimeters.

The silicon trackers, ECAL and HCAL sit inside a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T as shown below.

Below, the various path of detected particles in the layers of detectors:

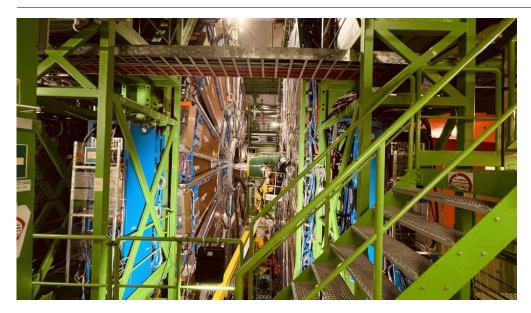


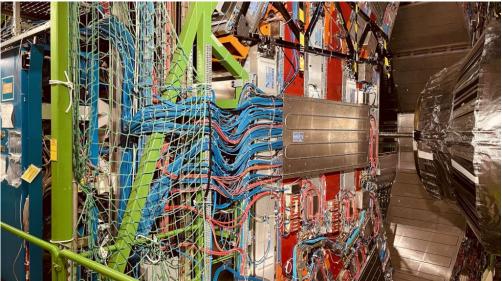
Below, a 3D view of the CMS layout:



One key difference between Atlas and CMS are their magnetic field. Atlas is using a toroidal magnetic field and CMS is using a solenoid field.

In the visit during the maintenance period, you can see more detectors than with Atlas, pictured below.





Below is what the superconducting magnetic foil is made of, with niobium-titanium wires embedded in an aluminum cast. It reminds me of the coaxial cables used to control superconducting qubits (for the NbTi part).



# More on CMS:

• Overview of the Phase 2 upgrade of CMS detector by Arnab Purohit, 2024 (27 slides).

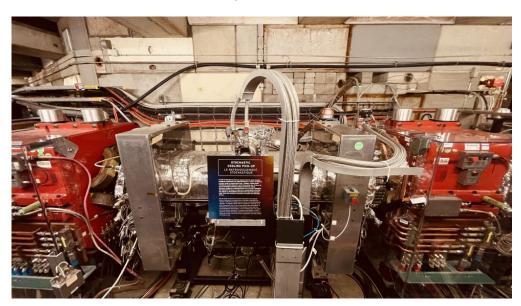
• The paper describing how the Higgs boson was discovered in CMS: Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, CERN, Physical Review B, 2012 (32 pages).

#### **Antimatter Factory**

I then visited the CERN "antimatter factory" that managed to generate antihydrogen and verify that these atoms were subject to the same gravity as normal matter, in the **AEgIS** (Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy) experiment in September 2023. It's big physics!

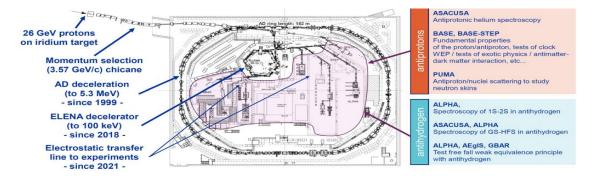


First, how is antimatter created at CERN? Antiprotons are created using high-energy protons from the Proton Synchrotron (PS) striking a metal target often made of nickel or iridium. These collisions generate secondary particles including antiprotons. A magnetic collection system then selects the negatively charged antiprotons and channels them into the Antiproton Decelerator (AD). The AD slows these antiprotons, after which the ELENA (Extra Low ENergy Antiproton) ring further decelerates them to around 100 keV, using various techniques like stochastic cooling (*pictured below*, in the ELENA ring). This gentler energy scale makes it easier for antimatter experiments (ALPHA, GBAR, and others) to capture and study antiprotons without immediate annihilation on surrounding materials.



Positron which are antielectron happens separately and come from radioactive isotopes that undergo ?? decay, or they use small-scale electron linear accelerators impinging on a "high-Z" (made of many Z bosons) target to

generate pairs of electrons and positrons. The positrons can then be slowed and accumulated in special Penning traps or buffer-gas traps, forming a stable reservoir for later combination with antiprotons to produce antihydrogen.



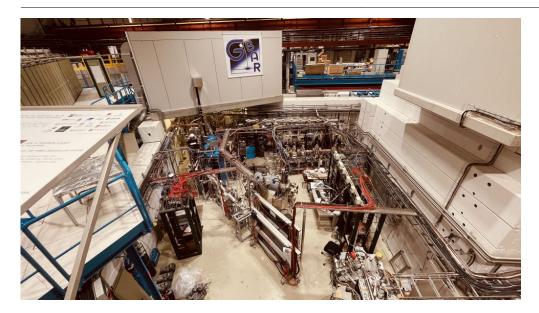
Below is a view of half of the Antiproton Decelerator hall, that is using antiprotons slowed down by the ELENA facility.



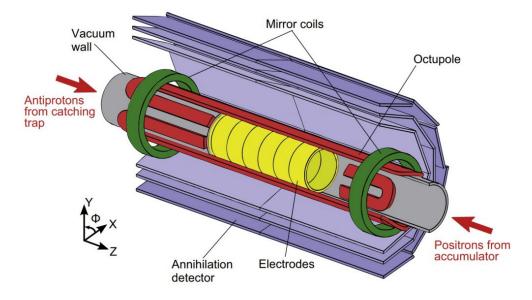
Below is the ELENA decelerator:



And the GBAR (Gravitational Behavior of Antimatter at Rest) experiment, which is part of AEgIS that measures the freefall acceleration of antimatter under gravity:



You may wonder whether antimatter can be stored. It can, and only in extremely small quantities. Since antimatter annihilates upon contact with ordinary matter, it must be confined in ultrahigh-vacuum chambers and held away from material walls by electromagnetic fields. The Antihydrogen trap (ATRAP) experiment compares hydrogen atoms with their antimatter equivalents. With the ALPHA experiment, small numbers of antihydrogen atoms have been stored for seconds to minutes using Penning traps for charged antiparticles like positrons and antineutrons (*below*), combining strong magnetic and electric fields. Penning traps are also used in trapped ions quantum computers! Neutral antihydrogen can be trapped in magnetic bottles traps. The ALPHA experiment has already stored antihydrogen for over 1,000 seconds in a magnetically neutral trap.



#### More on the antimatter factory:

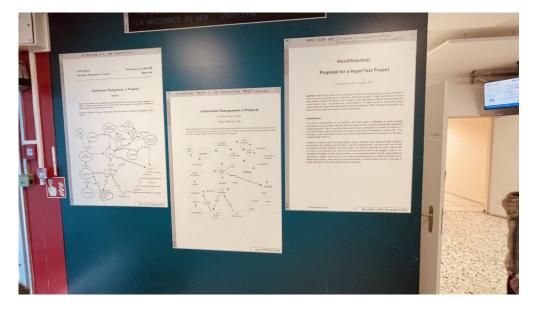
- AD/ELENA facility: status and prospects by D. Gamba et al, March 2024 (27 slides).
- The ALPHA antihydrogen trapping apparatus by C. Amole et al, 2014 (22 pages).
- Observation of the effect of gravity on the motion of antimatter by E. K. Anderson, J. S. Wurtele, et al, Nature, September 2023 (23 pages).

# Web story

At last, of course, you are remembered that the web and HTML were created at CERN by Tim Berneers-Lee in 1989. You got a plaque in a corridor next to his former office. You can't escape getting goosebumps about it!



As shown in the papers below, the creation of the web at CERN was not a random event coming out of the head of a single isolated researcher. It responded to a clear user need: share information and knowledge among a large community of international researchers scattered in dozens of countries and hundred labs. High-energy physics happens to be a non-commercial domain and a very open field. This required and open and standard architecture, thus HTML. The rest is History.



We could also quickly visit the CERN data center given a new one is under construction.



Indeed, all these experiments generate peta-bytes of data every year that are sifted through to find useful information.



That's all for this CERN visit!

Writing this long piece was quite an exercise. It's a "learning expedition" after the "physical expedition". Indeed, when visiting such a large infrastructure, you capture bits of insights and information, but the constructed mental image remains fuzzy. Researching a bit about it and writing such a post is a self-learning method. Sharing it makes it useful beyond my own ego and intellect!

Thanks for your long attention span!

Cet article a été publié le 27 janvier 2025 et édité en PDF le 29 janvier 2025. (cc) Olivier Ezratty – "Opinions Libres" – https://www.oezratty.net