# CMS at LHC

**Diego Barón**

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Universidad de Antioquia, Instutito de Física.

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# Motivation.

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Particle physics experiments can be made studying cosmic rays, solar neutrinos, dark matter in galaxies, etc.

**But don't forget accelerators...**
This experiments are the most popular because we can control almost all the initial conditions:

- The particles involved.
- The energy of the beams.
- The geometry of the experiment
- The amount of particles.

Experimental particle physicists must know and understand how experiments works in order to know:

- What to look for.
- And how to.

# The problem.

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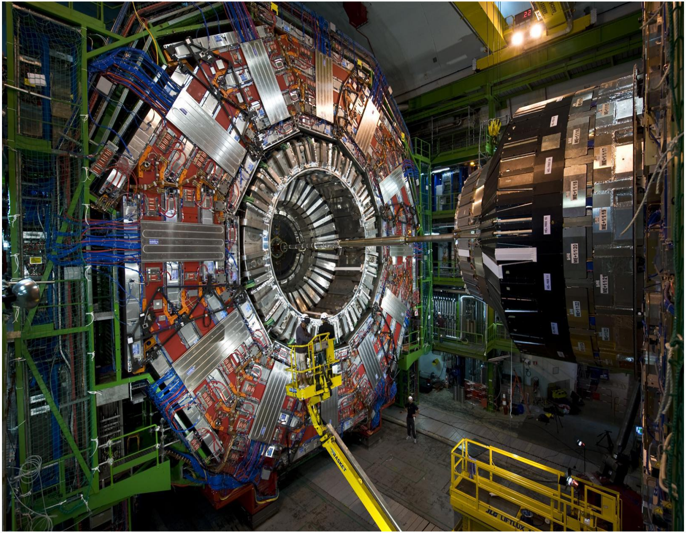


**The question is...**

¿How does CMS at LHC works?

# First LHC.

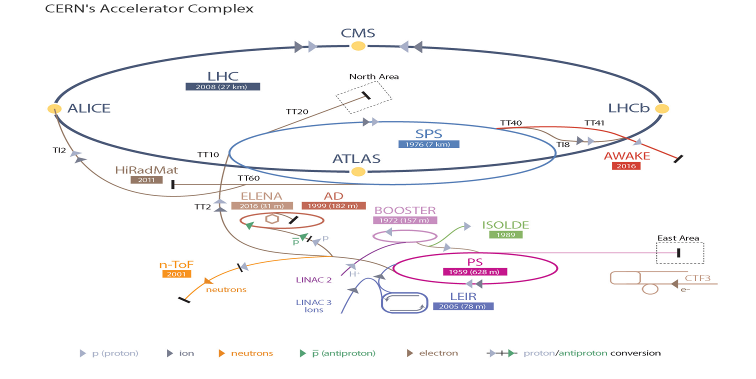
# LHC.

Is the main accelerator managed by CERN (European Organization for Nuclear Research). 21 member states-113 participant countries.

It's the biggest particle collider on Earth:

- 27 km circumference.
- 14 TeV at the center of mass. (8 TeV reached at Run 1)
- 100 m under the ground.
- 4 main experiments (detectors): ALICE,CMS,ATLAS,LHCb

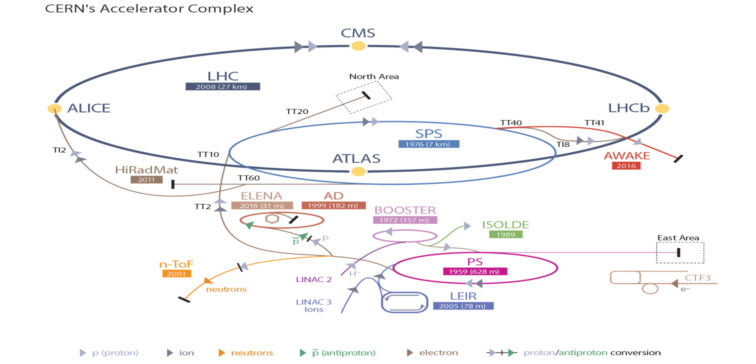
The two principal parts are the injector chain and the main ring.



# The injector chain.

Before reaching main ring, protons pass by a series of stages:

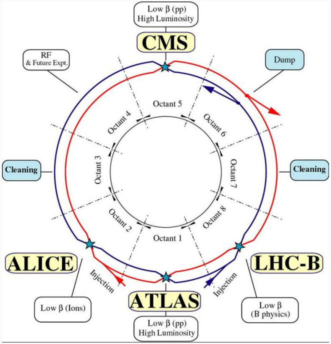
- Extracted via ionization of Hydrogen in the Duoplasmatron Proton Ion Source.
- Accelerated at 50 MeV in Linac2 (1978).
- Linac2 injects protons in the Proton Synchrotron Booster (PSB) and are accelerated up to 1.4 GeV.
- From PSB, protons are delivered to the Proton Synchrotron (PS) where they reach 28 GeV. They are also split from 6 initial bunches to 72, spaced by 25 ns.
- Finally, the pre-acceleration chain is finished by the SPS, the Super Proton Synchrotron. There, the bunches are accelerated up to 450 GeV.

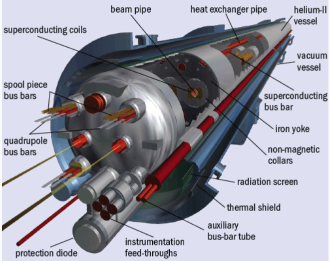


# LHC main ring.

It's composed of two rings that accelerate the proton bunches in opposite directions. Some characteristics of the design are:

- 15m magnets with an strong magnetic field of 8,33T.
- Superconductivity involved (1.9 K).
- Ultra high vacuum of $10^{-9}$mbar.
- In addition LHC has other magnets to correct different characteristics of the beams: 520 quadrupoles, 2464 sextupoles, 1232 octupoles.



# LHC main ring.

In collider experiments the main character is Luminosity:

$$L = \frac{k_n N_b^2 f_{rev}}{4\pi\sigma_x\sigma_y} R$$

In LHC design, this parameters have the following values:

| | |
|---|---|
| Energy[GeV] | 7000 |
| Luminosity[$cm^{-2}s^{-1}$] | $10^{34}$ |
| $k_b$ Number of bunches | 2808 |
| Bunch spacing [ns] | 24.95 |
| $N_b$ intensity per bunch [protons/bunch] | $1.15 \times 10^{11}$ |
| $f_{rev}$ revolution frequency [kHz] | 11.25 |
| $\sigma_x = \sigma_y$ Beam Standard Deviation [cm] | 7.7 |
| R Geometric reduction factor | 0.8 |

Cross section of a proton-proton collision at 14 TeV is 100-110 mb, 3 different processes are involved:

- Elastic scattering: Protons exchange momenta but their structure remains unchanged.
- Diffractive scattering: Momenta exchange but additional particles are generated apart from the final protons.
- Inelastic scattering: Partons interchange a big amount of momentum and produce several particles.

# LHC RUN 1.

On February 10th of 2013, the first run of LHC reached an end, this is called RUN 1, started on November 20th of 2009. The achieved center of mass energy was $\sqrt{s} = 8\,TeV$.

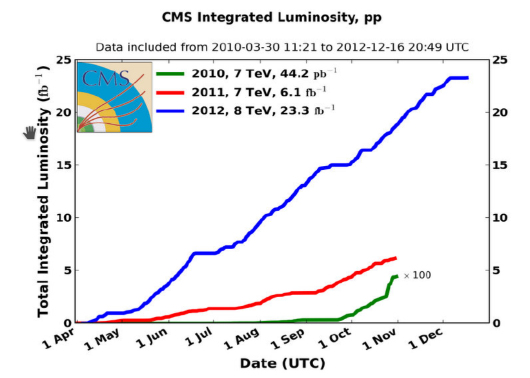


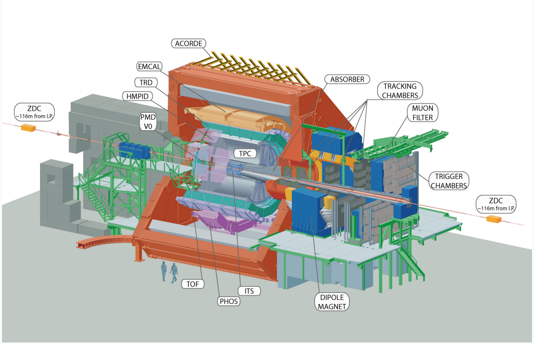

**Figure 1:** Integrated Luminosity at LHC RUN 1.

# Other experiments at LHC.

# ALICE.

A Large Ion Collider Experiment is located at point 2 of the LHC main ring.

Designed for Heavy Ions Physics.

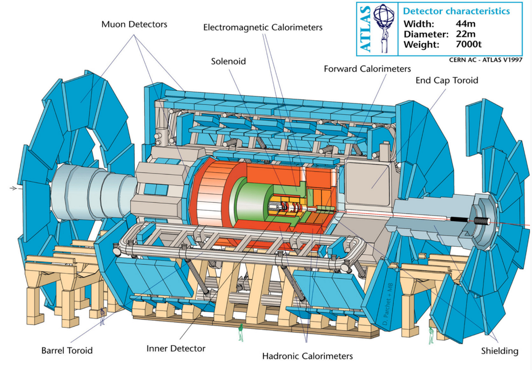



- H=16m,W=16m,L=26m. Weight=10000 Tons.
- Able to detect an extremely high number of tracks per event.
- Main subsystem: Time proyection chamber, a 90 $m^3$ gas chamber operated in a soleniod of 0.5T.

ALICE collaboration counts around 1500 people from 154 physics institutes in 37 countries.

# ATLAS.

A Toroidal LHC ApparatuS is the biggest LHC experiment, located at point 1.



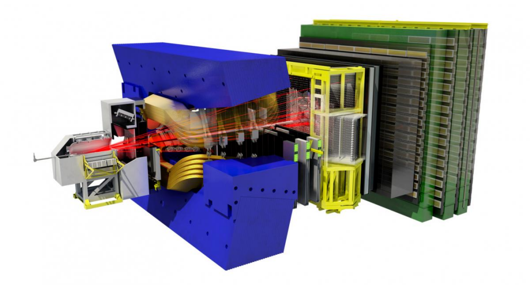

- H=25m,L=45m. Weight=7000 Tons.

  Its main components are:
- Tracker system.
- EM Calorimeter.
- Hadron calorimeter.
- Muon chambers.

ATLAS collaboration counts around 3000 people from 117 physics institutes in 38 countries.

# LHCb.

Located at point 8, it was designed to detect particles produced close to the beam direction. Smaller than CMS and ATLAS and conically shaped.



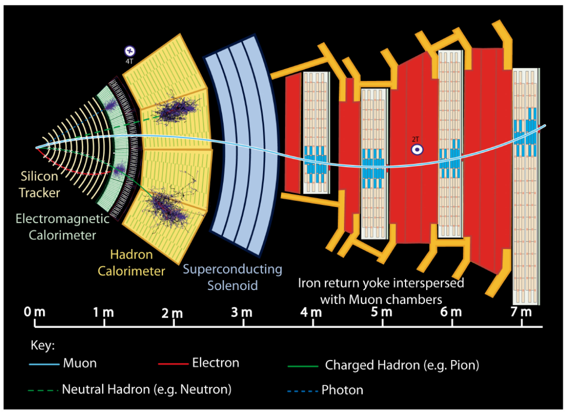
- H=10m,L=21m,W=13m. Weight=4500 Tons.
- It has a system to detect different type of Hadrons.
- Very precise vertex locator system.

LHCb collaboration counts around 700 people from 69 physics institutes in 17 countries.

# CMS.

# The Compact Muon Solenoid.

Located at point 5, its the second biggest LHC experiment, its called compact because the calorimeters are inside the magnet, and muon solenoid because it has a very precise muon detection system.

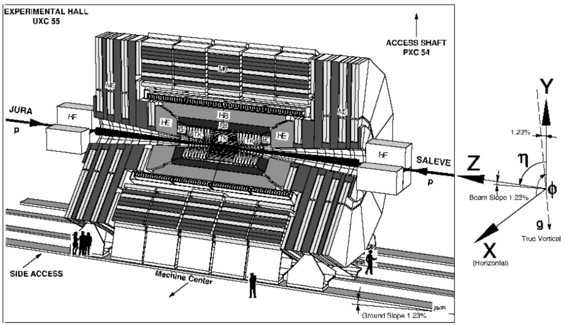



- H=15m,L=28.7m. Weight=14000 Tons.
- 3.8T magnetic field.
- The energy of jets wit $p_T > 20 GeV/c$ can be measured with 4% uncertainty.

CMS collaboration counts around 3500+3 people from 181+1 physics institutes in 41 countries.

# Coordinate system.

The coordinate origin is located at the center of CMS, in the "iteraction point".
Z axis: defined in the beam direction, poingting towards Jura mountains.
Y axis: defined towards the zenit. X axis: pointing to the center of LHC ring.
$\phi$ angle: Defined in x-y plane from x to y. $\theta$ angle: Located at z-y plane, from z to y.

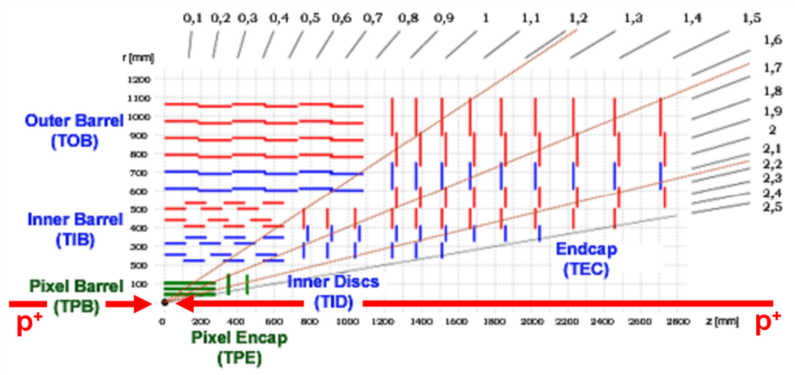



The commonly used momentum variables are:
1. $p_L$ Momenta in the z axis.
2. $p_T$ Momenta in te x-y plane.
It is always preferable to use pseudorapidity instead of $\theta$: $\eta = -\log\tan\left(\frac{\theta}{2}\right)$

**Magnet** The CMS has a large solenoid capable of producing a 4T constant magnetic field inside the 6m diameter and 13m long magnet. It weights 12000 and is made of 4 Layers of windings of NbTi cable at 4.45K to achieve superconducting state.

Outside the magnet 5 wheels and 3 disks of iron are placed to return the magnetic flux and inducing an external field of 2T.

Designed with two technologies: Pixels and Silicon strips, the pixels have a cell size of 100*150 $\mu m^2$ and the system achieves a resolution of $9\mu m$.
The efficiency is higher than 98% for all layer and disks, but it degrades with integrated luminosity.
Designed to reconstruc high $p_T$ leptons and as consequence photons, it can reconstruct secondary vertexes and has an efficiency from 85 to 95% for particles with $p_T$ between 0.1-10 GeV.
Constructed for being highly resistant to radiation, its expected to last for 10 years.



# Tracker system.

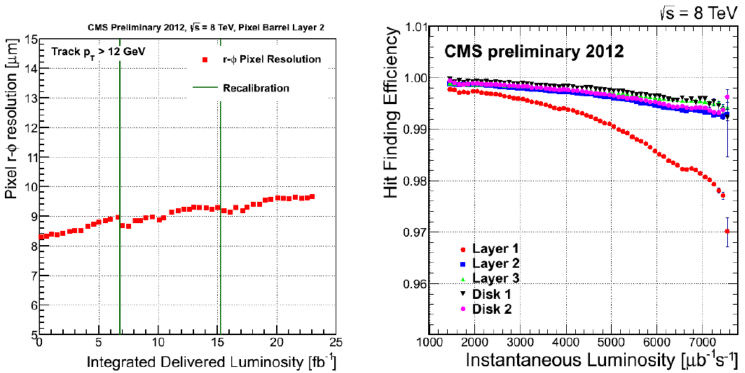
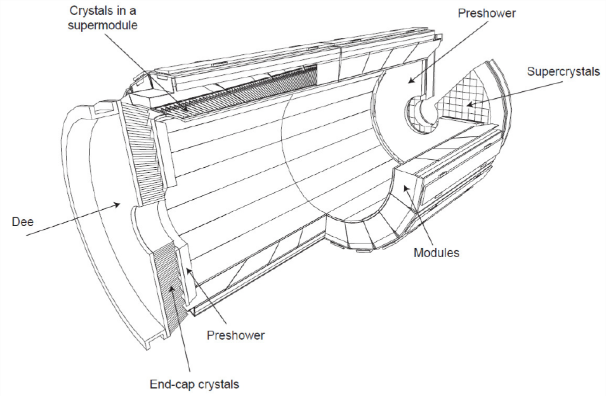



Figure 2.12: Resolution of the pixel detector in $r-\phi$ as a function of the luminosity delivered to CMS detector [left] and efficiency of finding hits by the same detector [right]. The hit finding efficiency is higher than 98% for the entire tracker. A degradation of pixel resolution is clearly visible as a function of the recorded luminosity. A high hit finding efficiency is important for a precise $p_T$ measurement [95].

# Electromagnetic Calorimeter.

The CMS ECAL system was designed to stop photons and electrons and measure their energy, it is a cylindrical hermetic calorimeter made of 61200 crystals in the barrel and 7324 in the endcap.
The crystal material is lead tungstate and was chosen for its short radiation depth, high density and fast emitting scintillation (25 ns). Its main disadventage is its highly dependent response to temperature. (2%/C)
This systems need constant correction because it loss of transparency due to radiation, the crystals aging is calibrated by a laser system.



# Electromagnetic Calorimeter.

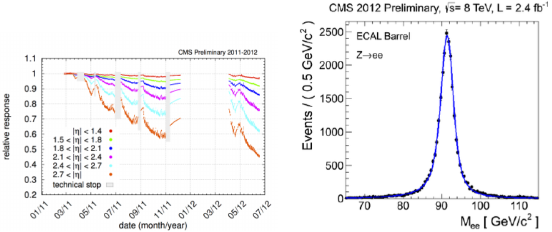
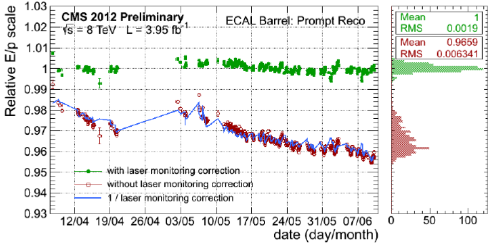


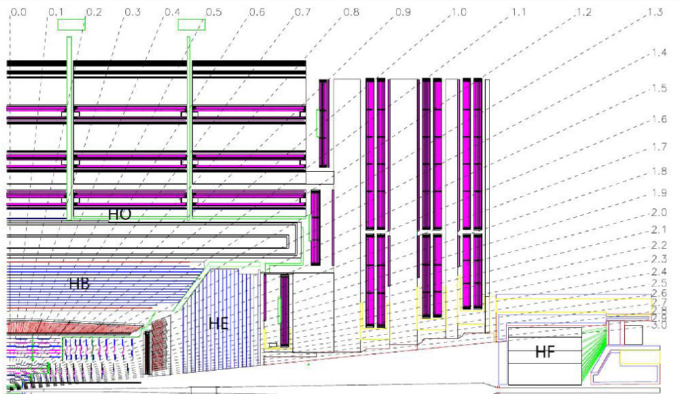

Figure 2.16: Relative response of the ECAL crystals as a function of time, for different $\eta$ regions [left]. Di-electron invariant mass from electrons identified in the ECAL barrel [right] [96].



# Hadronic Calorimeter.

The CMS HCAL is the subsystem made for hadron detection, its subdivided as:

- Hadron Barrel Calorimeter (HB): Covering $|\eta| < 1.4$ is located between the ECAL barrel and the magnet.
- Hadron Endcap Calorimeter (HE): Extends the coverage of the barrel in the region $1.4 < |\eta| < 3$.
- Hadron Outer Calorimeter (HO): Located outside the magnet.
- Hadron Forward Calorimeter (HF): Completes the coverage of the system from $|\eta| = 3$ up to $|\eta| = 5.2$.



# Hadronic Calorimeter.

The system is made of two parts: absorbers to develop hadronic showers and scintillators to measure particles energy.
The HB absorber is made of 40 mm thick steel plate, 8 layers of brass plates of 50.5 mm , 6 brass plates of 56.5 mm and a steel plate of 75 mm . The HE uses the same absorber but with thicker plates of 79 mm. Between the absorber plates a plastic scintillator, Kuraray SCSN81, 3.7 mm thick, is placed.

The produced light in the HB is collected by optical fibers and transferred to the Hybrid Photo Diodes (HPDs). These diodes were chosen because of their small sensitivity to the magnetic field, an important feature because HCAL is inside the solenoid magnet.

**High radiation problem at HF**

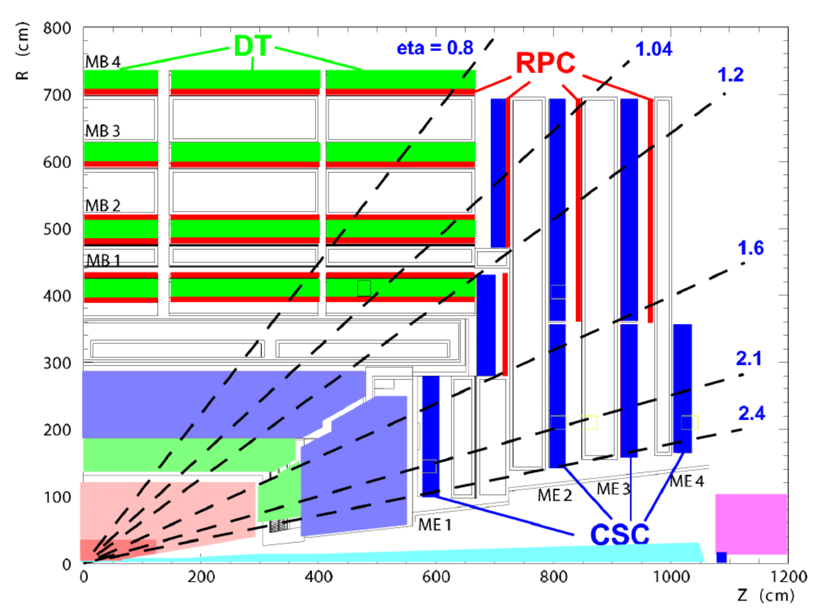
The HF design is different from the rest of the HCAL . The most important challengeis the high resistance to radiation from collisions: while in the central rapidity region, 100 GeV are deposited in average, in the forward region, is 760 GeV. For this reason a Cherenkov detector made of quartz fibers with a steel absorber was chosen. The light produced in the HF is collected by photo multipliers.

# Muon Chambers.

The muon detector systems is located at the most exterior layer of the dectector due to the high prenetration power of muons. The cambers are made of three subsystems:

- Drift Tubes Chambers (DT): located in the region with $|\eta| < 1.2$ and disposed in four layers. They consist of individual drift tubes of 50 $\mu$m of diameter anode wire with two electrode plates creating a drift electric field. The wall of the cell act as cathode. The cells are filled with a gas mixture, 85% Argon and 15% CO2 .
- Cathode Strip Chambers (CSC): installed in the endcaps, provide a coverage up to $|\eta| = 2.4$ from $|\eta| = 0.9$. These chambers are multi-wire proportional chambers made of six planes of anode wires with 7 cathode planes with a gas in the middle and perpendicular to each other. This system is able to measure with a precision between the 75 $\mu$m and 150 $\mu$m.
- Resistive Plate Chambers (RPC): This subsystem is made of gaseous parallel plate detectors. This detector is specially useful for triggering as it is very fast and have a good position resolution. There are 480 RPC distributed in 6 layers in the barrel with the DT and in 3 layers in the endcaps with the CSC, and covers the region with$|\eta| < 1.6$.

# Muon Chambers.



# Trigger.

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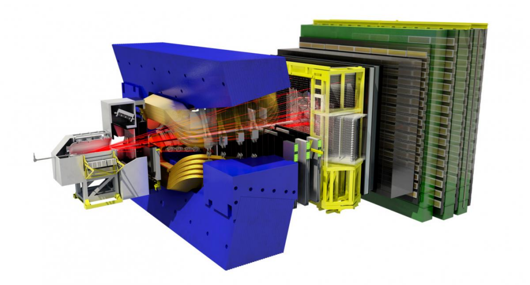

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