

Visiting LHCb and LHC

1 Visit itinerary and key messages

The visit itinerary consists of six points of interest:

1. On the way to pit 8 or upstairs

For suggestions and more information, see <http://.....>

To help you give an introduction to the visit above there are several posters in the SX8 building: the Big Bang story line that introduces the questions that we are trying to solve with the LHC, the international aspect of LHCb: 14 countries, 600 scientists, 47 universities and laboratories, 71 students, 35 companies, etc

2. DELPHI barrel

The DELPHI barrel is an excellent example of a collider detector (just like ATLAS or CMS, just smaller...) and it allows you to select a sub-detector to explain the principle of the instruments used in particle physics.

For details, see <http://delphi-expo.web.cern.ch/DELPHI-Expo/VisitingDELPHI.html>

Whereas in most other scientific fields (chemistry, biology, medicine, etc) the instruments are bought off the shelf, in particle physics we are obliged to develop new types of instruments. It often happens that these instruments later show up on the shelf ...

The DELPHI visitors' platform has one poster with an overview of the DELPHI detector and two posters explaining briefly the composition and the tasks of the LHCb detector.

3. LHCb electronics barracks

The itinerary allows the visitors to look into the LHCb electronics barracks. It gives the opportunity to say that we read out from the detector electronics 35 Gb/s over a conventional data network and that a farm of some 2000 PCs will be installed on the first level for the online processing. After the high-level trigger we record 70 Mb/s for further analysis.

4. Equipment shaft (which is usually off-limits in the cavern but may be seen in the SX8)

The shaft is 103 metres and measures 10 metres in diameter. The ATLAS and the CMS shafts measure 18 metres in diameter.

5. LHCb and the assembly site

(see below)

2 LHC experimental facility

The LHC experimental facility consist of the older CERN accelerator complex, the LHC accelerator and four(five) experiments ATLAS, ALICE, CMS and LHCb (TOTEM). The ATLAS and the CMS detectors are so called general purpose detectors aimed at discoveries, in particular of new particles such as Higgs, Supersymmetry, and things we least expect. The two detectors are built in a very general way but are not specifically aimed at making precision measurements. The reason for having two detectors is that discoveries need to be verified or falsified so it is very important to have a second setup that is able to see the same thing independently and preferably with a different method.

The ALICE experiment is a special purpose experiment dedicated to the study of lead ion collisions. A state of matter beyond ordinary plasma, that is when the temperature is so high that electrons are no longer attached to the atoms, has been predicted since a long time. It is called quark-gluon plasma and it would occur when the temperature and the pressure is so high that the quarks are no longer bound together in hadrons, such as protons and neutrons, but are asymptotically free to form a gas of quarks and gluons. Previous experiments at CERN have seen hints of this new state of matter but ALICE is set out to investigate this carefully. Colliding lead ions, stripped completely of all electrons (only 208 protons and neutrons) together means that a dense and hot ball of some 1200 quarks is formed. ALICE is built to study how this object behaves and how the hadronisation happens as the ball expands, namely how the quarks combine back into protons and neutrons and their heavier relatives again. It can be seen like a condensation of steam into water droplets as the steam is cooled by for instance expansion.

The LHCb experiment is also a special purpose detector dedicated to precision measurements on B-mesons (mesons containing b-quarks). In particular the experiment is set out to measure CP violation and to study rare decays of B-mesons.

The very brief Big Bang story on the LHC posters upstairs and in the pit situates the question that we will try to solve with the LHC.

3 LHCb aim

Very general – Situating the question

The following is again a story line but only from the point of view of “the matter of victory”.

The Universe began about 13.7 billion years ago as an extremely hot, dense and homogenous ‘soup’ of energy and particles. The energy was converted into particles of matter and antimatter. As pairs of matter and antimatter particles collided they annihilated each other, turning back into energy. For a short time there was a perfect balance, or symmetry, between matter and antimatter. However, as the Universe expanded and cooled it went through a series of drastic changes in its composition

Shortly after the birth of the Universe, the particles acquired their characteristic masses and a phenomenon occurred that differentiated matter and antimatter, causing asymmetry between the two.

10^{-11} s, 10^{16} K

One hundredth of a billionth of a second after the Big Bang, the quantity of matter in the Universe already outweighed antimatter, but only by one particle in a billion. At this stage the Universe was an opaque plasma of matter particles called quarks and anti-quarks, and force-carrying particles called bosons and energy carried by photons.

10^{-5} s, 10^{12} K

As the Universe cooled, this plasma condensed into hadrons, a class of particles that includes protons and neutrons. Matter and antimatter particles continued to annihilate each other into photons but the falling temperature meant that new particles were no longer produced. The Universe was left with more than a billion photons for each surviving proton.

1 minute, 10^9 K

It took just over a minute for the Universe to cool enough for the protons and neutrons to fuse together to form the first atomic nuclei.

380 000 years, 10^3 K

When the Universe had cooled to a temperature of a few thousand degrees, the atomic nuclei could capture electrons to form atoms. This made the Universe transparent. The radiation from this epoch can be detected today as the afterglow of the Big Bang - the so-called cosmic microwave background.

500 million – 1 billion years, 18 K

The first stars were born like beacons in an otherwise pitch dark Universe. Galaxies formed, and the Universe continued to expand.

13.7 billion years, 2.7 K

Today, at a temperature of just 2.7K, we see a Universe made entirely of matter. All astronomical searches for celestial objects made of antimatter have failed.

Very general – What is the answer?

In 1966 Russian physicist Andrei Sakharov outlined three conditions necessary for the matter to predominate in the Universe, one of which says that there should be a measurable difference between matter and antimatter - the mirror image is not perfect. Observations of certain particle collisions have shown that the mirror symmetry is imperfect in about one in a thousand collisions (kaon system). In technical terms this is called “CP violation”. 45 minutes will not allow you to go into details but some people may have heard about the term. Other observations, however, tell us that this is not sufficient to account for our Universe.

The full explanation for this imperfect symmetry looks like being new physics that could be revealed by achieving collisions at higher energy – by recreating the moment, 13.7 million years ago, when particles called beauty and anti-beauty quarks were produced in pairs.

The LHC will accelerate particles to the highest energy ever achieved in a laboratory. The LHCb detector will register the collisions between these particles, which replicate the conditions when the Universe was only a hundredth of a billionth of a second old.

4 LHCb cavern and LHC tunnel

- Cavern length 70 m
- Cavern floor width 15 m
- Cavern maximum width 20 m
- Height 18.60 m
- Diameter of LHC tunnel 3.50 m close to interaction point

5 LHCb detector

Since the anti-beauty-beauty quark pairs produced in each collision travel out close to the accelerator, the LHCb experiment is actually a series of detectors mounted close to the accelerator one behind the other over a length of 20 metres. This means that from collision point to the muon chambers, the LHCb detector is as big as ATLAS...☺ It's just that LHCb consist of only an endcap. The DELPHI endcap on the DELPHI poster can be used to show the difference between a full space-angle detector and LHCb. In total LHCb weighs about 4500 tonnes.

LHCb will record about 10 billion pairs of anti-beauty and beauty quarks per year extremely precisely to try to detect a bigger asymmetry that will help explain how it is that nature prefers matter to antimatter.

Despite being very big and heavy, the LHCb detector is a high-precision instrument based on the latest cutting-edge technology. The size comes from that fact that, at a closer look, it actually consists of several different types of sub-detectors, each one specialized at measuring a different aspect of what happens in the particle collisions. As a whole, the detector provides information about the trajectory, the identity, the momentum and the energy of each particle produced in the collisions. Each sub-detector is also very big in order to make precise measurements of the extremely fast and energetic particles that are produced.

The whole LHCb detector will cost approximately 75 million CHF. Don't forget to mention that this installation is shared between almost 50 universities in 14 countries! And over many years, 5-10 years of use?

Tracking

The topology of the particle reaction is recorded using tracking detectors. LHCb has four trackers: VERtix Locator (VELO), Silicon Tracker (ST), Outer Tracker (OT) and muon chambers (MUON).

Energy

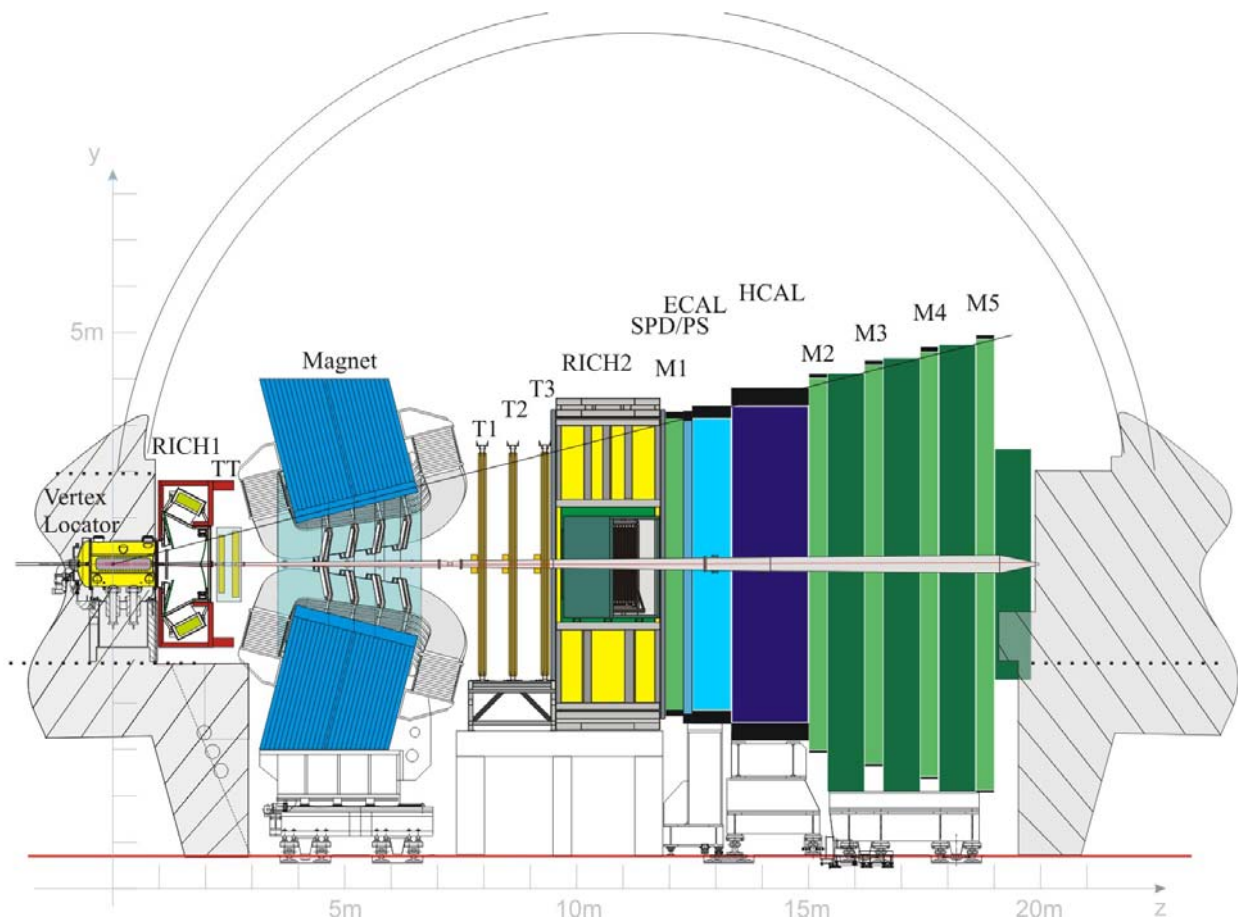
The energy of each particle is registered using calorimeters. The LHCb calorimeter system consists of a PreShower (PS) and a Scintillator Pad Detector followed by an Electromagnetic CALorimeter (ECAL) and a Hadron CALorimeter (HCAL).

Momentum

The momentum of each charged particle is obtained by measuring the curvature of the particle trajectory as recorded by the tracking detectors in a magnetic field.

Identification

The particles are identified by the signatures they leave in different type of detectors. The LHCb particle identification is based on the Vertex Locator, two Ring Imaging CHerenkov detectors (RICH1 and 2), the calorimeters and the muon chambers. The other tracking detectors also provide clues.



5.1 Vertex LOcator

The VELO tracks the particles close to the collision with a precision of $\sim 10\mu\text{m}$ to find decays of particles containing b-quarks. Finding B-mesons is based on finding secondary vertices that is a short distance away from the primary collision vertex. Typically the B-mesons may travel as far as 1cm before decaying (1.6 ps lifetime). The high track resolution means that the flight distance can be reconstructed so precisely that a proper lifetime resolution of 40 fs is achieved.

The VELO consists of a row of 0.3mm thick silicon detectors (21) measuring the particle trajectories in cylindrical coordinates (r , ϕ , z) and has 22.000 signal cables which carry data from some 200 000 sensor channels. The sensitive area of the silicon plates starts at about 8mm from the beam line. During the injection the detector must be retracted by 30 mm from the beam to avoid possible damage.

The Pile-Up system consisting of a veto detector similar to the VELO ensures that bunch crossings with only one proton-proton interaction is recorded by veto'ing multiple interaction crossing in the first level trigger (L0).

5.2 Silicon Tracker (ST)

The Silicon Tracker consists of a Trigger Tracker (TT) and an Inner Tracker (IT). The TT is based on silicon microstrip detectors and it has the task of tracking low-momentum particles which are bent out of the acceptance of the experiment by the magnetic field such that they are not detected by the Inner Tracker and the Outer Tracker. In addition the stray-field from the magnet allows the transvers momentum to be estimated for tracks with large-impact parameters in time for information to be used in the L1 trigger decision

The three stations of IT are also based on silicon microstrip detectors and they have the task of tracking particles that travel close to the beam line.

5.3 Magnet

Despite the fact that the LHCb magnet is a conventional warm magnet and not supraconducting, it provides a field of 4 Tm over the entire acceptance of the experiment with a power consumption of 4.2 MW. The polarity can be changed in order to eliminate systematic errors that can enter into the precise measurement.

The magnet contains two coils, each weighing 27 tons, mounted inside a 1,450-tonne steel yoke. Each coil is 7.5m long, 4.6m wide and 2.5m high, made of a pure aluminium conductor which is 50 x 50 mm². The conductors have a 24mm bore to circulate cooling water through the entire magnet.

5.4 Outer Tracker (OT)

Together with the Silicon Tracker, the Outer Tracker form the main tracking system in LHCb. The tracking is needed to reconstruct the charged particles and measure their momenta in the magnetic field. The tracking is also crucial to know the direction of the particles which produce Cherenkov light in the RICHes and to associate calorimeter showers to either charged or neutral particles, and to associate tracks in the VELO with muons seen in the muon detectors.

Each station of the OT is based on four layers of detector modules measuring X,U,V,X. The two central modules are installed with a stereo angle of $\pm 5^\circ$ with respect the x-measurement plane. Each detector module consist of 5mm straw tube drift chambers in two layers which are staggered with respect to each other and which are packed into a gas-tight box.

5.5 Ring Imaging Cherenkov detector (RICH1 and 2)

The RICHes are based on several types of radiators in which charged particles emit Cherenkov photons in the form of a light cone around the particle trajectory. The angle depends on the velocity of the particles. Focusing mirrors reflect the Cherenkov photons onto position sensitive photon detectors such that the angle can be measured. Knowing the momentum of the particle allows computing its mass which is unique for its identity. To satisfy the physics aim of LHCb, the RICH photon detection must be cable of resolving single photons down to an angle of ~ 0.02 degrees over an area of 2.6m^2 !

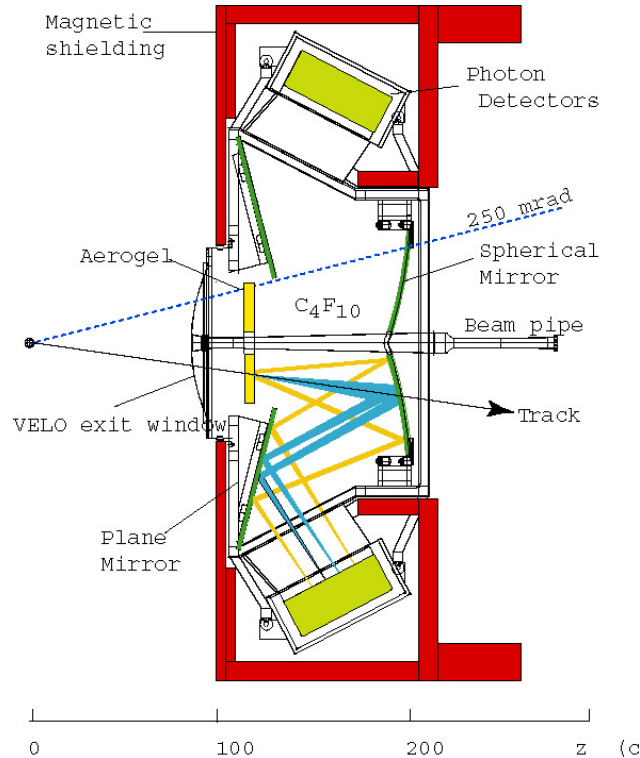


Figure 1: Structure of RICH2

5.6 Electromagnetic and Hadronic Calorimeters

The main purpose of the calorimeter system is the identification of electrons, photons and hadrons and the measurement of their energies and positions.

The electromagnetic calorimeter (ECAL) is based on modules (about $12 \times 12 \times 41 \text{ cm}^3$) containing a stack of 66 layers of 2 mm lead and 4 mm scintillator plates (“Shashlik” structure). There are ~ 3300 such modules weighing about 30 kg each, that is in total ~ 100 tonnes. Each module is traversed by either 64 (outer modules) or 144 (middle and inner modules) WaveLength Shifting (WLS) fibres which are read out at the back of the structure by photomultipliers. The ECAL covers an area of 50 m^2

Electrons, positrons and photons interact in the lead layers and produce showers of particles. The charged particles (electrons and positrons) in the shower produce scintillating light in the scintillators which summed up is proportional to the energy of the incoming electrons, positron or photon.

The electromagnetic calorimeter is preceded by a Scintillator Pad Detector (SPD) a PreShower (PS) detector. The SPD and the PS signal the presence of charged particles.

The HCAL principally identifies and measures energy of particles containing quarks, ie hadrons. It consists of tile structure of iron and 3mm scintillating plates which is parallel to the LHC beam pipe. A hadron interacting in the iron produces a shower of particles in the structure. As in the case of the ECAL the charged particles in the shower produces scintillating light which summed up is proportional to the initial incoming hadron.

The scintillation induced by the particles is also readout via WaveLength Shifting (WLS) fibres. In total the HCAL has 80 km of fibre and weighs ~500 tonnes.

5.7 Muon chambers

As muons are present in the final states of many CP-sensitive B-meson decays, muon detection is a fundamental requirement of the LHCb experiment. The muon system consists of 5 stations of Multi-Wire Proportional Chambers ranging from $8 \times 6 \text{ m}^2$ (M1) to $12 \times 10 \text{ m}^2$ (M5), and thus a total surface of 435 m^2 . The total number of wires in the chambers is about 2.5×10^6 , which corresponds to a total wire length of about 1200 km (30 μm thick). The innermost region where the radiation and particle rate is the highest consists of Gas Electron Multiplier (GEM) detectors. A total of 126000 front-end readout channels are used.

In between each muon station there is a muon filter (being assembled in the cavern) consisting of iron blocks. The muon filter serves to attenuate hadrons, electrons and photons to minimize “punch thrus” behind the calorimeters which can lead to muon misidentification. The total weight of the muon filter is 2100 tonnes

5.8 Trigger and data acquisition

The LHCb detector registers particle collisions at a rate of 40 million per second. The readout system comprises three levels of triggers to reject uninteresting events, two of which are high-rate triggers. The first level trigger decision (L0) has a latency of 4 μs meaning that 160 events has to be stored while waiting for the decisions to arrive. The trigger decisions are based on information from the Pile-up system, the calorimeters and the muon chambers. The trigger is implemented in hardware (L0 trigger processors and L0 decision unit) and selects about 1/40 events, that is the accept rate is ~1 MHz. The second level trigger (L1) runs on the online processing farm and has a variable but a maximum latency of ~52 ms meaning that up to ~58 000 events may need to be stored while waiting for the decisions. The L1 decision is based on information from the VELO, the TT, and muons and calorimeter clusters as provided by the L0 decision unit. The selection is about 1/25 leading to an L1 accept rate of 40 kHz.

The High Level Trigger runs on the online processing farm and is supposed to reduce the data rate to 200 Hz which are stored on tape.

The data acquisition system is able to cope with a data rate of 12 Gbytes/s – equivalent to 17 CDs per second.

6 LHC accelerator

The general idea at CERN is to use older accelerators as pre-accelerators for the latest accelerators.

The latest accelerator called the Large Hadron Collider (LHC) will go online in 2007. With its 27 km circumference it is the largest accelerator in the world. It collides beams of protons going clockwise in the accelerator with beams of protons going anti-clockwise. The protons are injected in to the accelerator from the older accelerators at CERN. Each beam consist of about ~2800 groups or bunches of about 100 billion protons. The bunches make ~11 000 turns per second with a speed that is more or less the speed of light. Light would win with about 40 cm on an around-the-world competition with the protons (40 000 km). The bunches are typically located 7.5 meters behind each other which with the speed of light corresponds to 25 ns, that is the experiments will see bunches of protons meeting 40 million times per second.

The protons run in separate ring except at the experimental installations where they cross. It takes about 4.3 minutes per ring to fill the accelerator. It is hoped that we can maintain the beams colliding for ~10 hours before the intensity decreases to a value where it is better to refill.

The energy of each proton is 7 TeV which is actually ~100 times more (!!) than the kinetic energy of a mosquito (1 mg, 0.1 m/s ~ 10^{-8} J ~ $3 \cdot 10^9$ eV). A mosquito contains 10^{19} protons....

In total the energy stored in the LHC beams is 360 MJ. This is the energy of a car moving at 3000 km/h carried by 10^{15} protons which weighs all together ~ 10^{-9} grams. (1 g of hydrogen, essentially protons, has $6 \cdot 10^{23}$ protons)

The transversal size of the beams at nominal energy at the IPs is about 17 μ m (RMS) and the longitudinal length is about 6 cm (RMS).

Whereas the luminosity at the LHCb collision point is tuned to limit the number of proton interactions to one, ATLAS and CMS see up to 20 pairs of protons interacting per bunch crossing, that is 800 million interactions per second...

The whole accelerator, 36 000 tonnes, will be cooled down to 1.8K which makes it the "coolest" object in the Universe (Cosmic Microwave Background radiation at 2.7K). Initially 12 million litres of liquid nitrogen will be used and then they will switch to 800 000 litres of superfluid helium. Each magnet is 15 metres long and will undergo a contraction of 4.5 cm each!

The LHC accelerator will also occasionally run lead ions at an energy of 1150 TeV. This means an energy of 2.76 TeV per nucleon. 592 bunches of will contain about 10^8 lead ions each.