Information for guides

for the CERN Open Days on 14-15 September 2019

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1. Introduction

This document is intended to provide you with material on which you can base your discussion with the visitors, along with more detailed background information for those not familiar with LHCb. It is not be intended to provide a word-by-word account of what an ideal visit underground should contain, nor what you should say on the surface. Everyone is specialized in different fields and the best is to convey the key messages from a personal and enthusiastic angle, and react to the response from your group.

We will have different categories of volunteers: guides bringing people on the underground and surface pathways, undergrounds and surface crowd marshals, gate agents, information agents, etc.

While this document is mostly intended for guides everyone is encouraged to answer visitors questions and explain what we do at CERN and at LHCb while carrying out their volunteers' primary tasks and can find some information here.

The main idea is to explain what the visitors can see, at each stopping point of the itinerary. Similarly on the surface itinerary you should explain what people see at the various points and put in the context of the experiment.

Discussions of more abstract concepts such as particle physics, the Standard Model, etc., should be done on the surface when moving from one visit point to the other or while waiting for the visit to start.

Sections 3 to 5 are mostly intended to help along the tour. Each of these sections will give you a general suggestion and some points that may be of interest. The idea is not for you to say everything that is written here but give you some hints of what may be interesting. The best is that you adapt what you say to the interest of the group you are guiding.

- Section 3 cover the first part of the surface tour, i.e. the LHCb control room and the exhibit
- Section 4 cover the underground tour.
- Section 5 is for the rest of the Point 8 surface tour, i.e. the LHCb assembly hall and data center and the CAST experiment[1]

The later sections gives some general background for the LHC, the LHCb experiment and detectors and the DELPHI experiment. They could be useful for any volunteer.

Some summary facts and numbers are listed at the end in Sections 11 and 12.

2. When you first meet the visitors

If you are a guide you will first meet the group of visitors at the 'Group Forming Point'. The first thing you should do is to introduce yourself, then check they are all present.

You will have some minutes while they collect their helmets and put their bags in the lockers as well as when you walk to the LHCb control room, the first stop in the visit pathway. You can use this time and that on the lift going underground to give visitors some general information.

A volunteer "gate agent" will be at the "wardrobe" to help you remind the visitors that only small bags are allowed underground. You also have to remember to lock the box and take its key with you! This is where you and a gate agent will do the last check to verify they have closed and flat shoes; in case of need there will be some spare shoes for them to use.

You should also remind the visitors to respect the safety rules they were given: they will need to always stay with you and the rest of the group, while underground they will need to keep their helmet on their head at all times and cannot drink or eat while in the cavern. Warn them that they will have to climb some steep stairs and the elevator is rather small for the big group they are in case some of them would suffer from claustrophobia.

If someone could not join the visit underground they will be with you until during the surface visit, but inform the "gate agent" so that someone will come at the PZ lift to take care of the person(s) staying on the surface before you go underground with the rest.

Introducing yourself. People may have "stereotypical" ideas of a laboratory and what a researcher and people working at CERN looks like. Let them know what you do when you introduce yourself and explain that not only researchers but also technicians and engineers in many different fields and other people work at CERN.

Where are they? You can start out mentioning that the site they visit is nothing but a modern laboratory where the table-top experiments have been replaced by larger scale instruments. Explain with a few words that they are at Point 8, one of the interaction points for the LHCs counter-rotating beams, the home of the LHCb experiment.

What is particle physics? It's about continuing seeking the answers to the same questions that man asked himself as soon as we acquired consciousness. Today it has become more specifically the quest to understand the fundamental particles and interactions in order to build a model that can help us to understand the evolution of

[1] While CAST is part of the guided tour details are not covered here as they will be given by their dedicated guides.

the Universe. By looking out in the Universe with various instruments such as telescopes we can explore the Universe back to about 400 000 years after the Big Bang. To understand the first 400 000 years we have to rely on experiments in which we try to recreate the conditions of the early Universe in small scale and study the behavior of particles and interactions. The "how to do this" comes naturally and the answer is CERN and particle accelerators.

What is CERN? First of all it is a laboratory that provides accelerator beams with which physicists can do experiments. A second key message is the international aspect of CERN. In the post-war world one of CERNs major tasks was to stimulate international collaboration. It also functions as a knowledge bank beyond economic and political interests. CERN has 23 member states "owning" CERN. However many other also non-European countries are involved in different ways. Researchers of 110 different nationalities from more than 70 countries come to profit from the CERN infrastructure, to make experiments and develop the technologies required to make them. Some also contribute to the accelerator's complex. Few scientists are employed; out of over 12200 only about 2500 are employed by CERN, this include everybody, only about half are physicist and engineers! The others scientists come from universities and institutes around the world contributing with a large turnover and exchange of knowledge and ideas, and they disseminate this information in teaching at universities, in collaboration with national industry and to the public.

What are the experiments at CERN? There are many experiments at CERN and not only at the LHC. The main experiments at the LHC are ALICE, ATLAS, CMS and LHCb but there are also three smaller one that make use of the collisions produced in the others (TOTEM, LHCf and MoEDAL, the last one is hosted by LHCb!). If you want you may mention that some of the smaller experiments study nuclei and atoms (ISOLDE), antimatter by making and studying atoms of anti-Hydrogen (ATRAP, ASACUSA), or the relation between cosmic rays and the formation of clouds (CLOUD).

Around the LHCb Exhibit there are posters that can help explaining some of these points.

3. LHCb surface visit

While you walk to the LHCb control room you may want to tell people you will first have a short visit of the LHCb control centre and the exhibit were they will see samples of the LHCb sub-detectors before going underground in the experimental cavern.

You have 15' to spend in the Control Room and Exhibit combined.

3.1 LHCb control room

The LHCb control room is where the experiment is controlled and monitored. During regular operations, the LHCb experiment is "taking data": this means that the detector is turned on, the collisions are recorded in the detector and the data is stored away for physics analysis.

To do that, the experiment relies on a shift crew of two people: a Shift Leader and a Data Manager. Such crew remains in charge for 8 hours until a new crew of two people takes over and again the rotation happens after another 8 hours. Such rotation happens 24/7 as long as the accelerator is on and providing useful data, holidays included. The crews are composed by collaborators of the LHCb experiment, about 400 people were trained and took shifts during the first decade of operation of the LHCb experiment: the average number of 8 hours shift taken by one collaborator per year is ~4, which means that a collaborator only has to take 4 shifts in the whole year to operate LHCb.

Because of this, the LHCb experiment has developed a very robust and automated control system, based on an industrial software (WinCC from Siemens) that is able to automatically monitor, control and operate the experiment without the direct help of the shifters. The shifters are mostly alerted by messages, voices and alarms when something happens and in certain cases, only asked to acknowledge the action. To make sure she/he is aware of what is happening (and to make sure she/he is paying attention).

The Shift Leader sits towards the left of the control room and her/his role is to be in charge of the safety of the personnel in the LHCb area and the detector. In addition, the Shift Leader monitors the actions of the automated control system through custom-made software panels which are located on the screen right in front of her/his seat. The Shift Leader is also in charge of performing actions if necessary. If a problem arises, the Shift Leader is supported by a battery of experts on call: they can be called at any time of the day and night to help her/him get through the problem. Communication is normally done through phones including a direct "red phone" line to the control room of the LHC in case we need to communicate with them.

The Data Manager sits towards the left of the central aisle of the control room and her/his role is to monitor the quality of the data that is being recorded by the detector. Automated software jobs run on the real-time data that is being collected and generate a set of information that are used by the Data Manager to decide if there is a problem or not.

The information are generally shown to the shift crew via the usage of computer screens that show plots, graphs, alarms, messages, information, colors, shapes to help the shifter understand what is going on.

To the back of the central aisle, the infrastructure monitoring section can be seen. It has information related to the access system, to the cooling and electricity and the emergency safety panel, which is still based on old-fashioned robust buttons that can be pushed in case of ultimate needs (for example, if the control system does not respond or if there is a power outage in the surface but not in the cavern).

After this period of shutdown, the LHCb experiment will be upgraded to better, faster and more efficient detector. Next year, in 2020, we will need to "commission" the detector again. This means, we will need to put together all the new pieces, power them, interface them to the control system and operate them accordingly.

This is when the rest of the control room and screen are used. These are dedicated to sub-detectors experts and the control room will be very lively next year and in 2021 when we will restart after the shutdown.

3.2 LHCb exhibit

Once you accompany your group from the control room to the exhibit is a good time to say that LHCb is undergoing a major upgrade. In order to make even more precise measurements we are replacing more than 60% of the sub- detectors. We are also replacing the read out electronics of all the detectors as well as the Data Acquisition system and the trigger

Here you can choose what to show them: the event panels on the wall with some of the LHCb physics results, the models of the detector and the cavern, the samples of the RICH HPDs and mirrors, the Silicon trackers or the muon chambers, the calorimeters modules, the Outer Tracker and Scintillating Fibres modules…

In some cases samples of the new detectors to be installed are shown side by side to those that have been used up to this Long Shutdown: it is the case for the VELO old r-phi strips' sensor and the new pixels' sensor; for a RICH's old HPDs photon detector and a new MaPMTs elementary cell; for a module of the old Outer tracker close by one to one module of the new Scintillators Fibres tracker.

But don't miss the VELO in front of the picture of the LHC tunnel exactly as it is just upstream of the VELO detector in the LHCb cavern!

The VELO two detector halves shown there are a 'hot spare' of the one that took data in Run1 and Run2. They were ready to be installed in case there would be a problem with the one in the cavern. That is because the silicon modules move: they are kept at 30mm distance from the beam when the protons are injected and accelerated in the LHC and go closer once collisions have been established, In Run1 and Run2 the VELO halves went to a 7mm distance but the new one will go even closer in Run3 to a 5mm distance. It is in fact the detector of the four LHC experiments that goes closer to the collisions! But if the beam would move out of its path it would be very dangerous for the detector hence the need of a ready to go spare.

The model of the whole UX85 cavern is located in the movie theatre and you can use it to give a preview of what they will see underground.

You can find more explanations on each detector in section 10 or in the "LHCb Exhibition, Guide for guides".

4. Underground Visit

You may want to take advantage of the ride down on the lift to tell people that you will explain what they will see, that there will not be much time for questions but that they can pose them when back on the surface. You should also remind them that will need to always keep the helmet on their heads while underground and that they are to stay with the group. While they should not touch any equipment, they are welcome to take any picture they want.

One point of interest may be that the cavern is 103m underground. They can actually see the depth they are while descending on the elevator monitor. A point of curiosity may be that the LHCb cavern is the deepest of all the LHC caverns: this is because the tunnel is not parallel to the surface but has been built with an inclination to adapt to the geological structure of the ground.

Before going down the crowd marshal will help you doing a last check that all visitors are wearing appropriate shoes and have an helmet on their head.

In case someone from your group cannot join the visit underground another volunteer will be at the top of the PZ with the crown marshal to take charge of the visitor staying on the surface.

4.1 DELPHI barrel

The first point of interest exiting the PZ safe area is the DELPHI barrel.

The LHC tunnel was built for an earlier accelerator, the Large Electron Positron (LEP). LEP was – and still is – the largest electron-positron accelerator ever built. Four experiments took data at LEP. One of them, DELPHI, was located where the LHCb detector now sits. It was decided to keep it in the cavern, just moving it to the side; visitors here will see a piece of CERN and particle physics history.

There is a big panel on the left going out of the door with indicated where the DELPHI and LHCb detectors are probing in the universe evolution, in case you have to wait here.

The visit path goes upstairs on the DELPHI visitors' platform where you will stop for 5'.

The DELPHI barrel is an excellent example of a collider detector (just like ATLAS or CMS, just smaller…) and it allows you to explain the principle of the instruments used in particle physics. Whereas in most other scientific fields (chemistry, medicine, etc) the instruments are bought off the shelf, in particle physics we are obliged to develop new types of instruments. It sometimes happens that these instruments later show up on the shelf…

On the other side of the platform hanging on the wall there is a real size image of one of the DELPHI endcaps so that visitors can be 'in' the detector.

Few messages you can convey here are:

• LEP had energy 100 times lower than the LHC and ran from 1989 to 2000. It produced specific type of particles, Z^0 and $W^{+/-}$ to make precisions measurements of their characteristics. These particles were first observed at CERN in 1983 at the Super Proton Synchrotron (SPS)
that is now used to inject protons in the LHC.

• DELPHI was one of the four experiments at LEP and was housed in this interaction point, now occupied by LHCb. Its barrel part, weighting 3200 T, was moved to its current place on an air cushion (used later for CMS) to maintain it as a visitor attraction during construction of the LHC and after LHC start up.

• DELPHI used to be one of largest particle physics experiments, now small compared to LHCb and dwarfed by ATLAS (which is 25m high while DELPHI is about 11m).

• Its detectors are arranged in cylindrical layers around the beam-pipe: vertex detector, tracking chambers, RICH, solenoid magnet, calorimeters, muon detector.

• Here you have the opportunity to point out that each detector is specialized in a given measurement; physicists need to combine the information from all the detectors to get the whole picture of what happens when the protons collide. While the picture is made of electronics signals it is not so dissimilar to those they are taking.

• You can also see the DELPHI vertex detector with its silicon layers as they would have surrounded the collision point on the side. The LEP experiments were the first where silicon detectors were used extensively in particle physics, although they were used before in fixed target experiments.

• LHCb has a different geometry, like a slice taken out of the DELPHI barrel and rotated to go in the same directions as the beam, but the detector principles are similar.

4.2 Walking toward LHCb through the chicane

Going down the stairways from DELPHI you will walk through the experiment access system and arrive to the experimental cavern.

You can mention that when the LHC is switched on radiation is present and no one is allowed in the detector side of the cavern. People working in LHCb that need to access the detector can do so when beam is not present through the dedicated access via the chicane you walk through. The chicane crosses a concrete wall (3.2 meters thick) that separate the experimental hall from the one where DELPHI is. The wall is there to shield people, some of the electronics and the services of the experiment (e.g. gas and cooling plants). Even when the LHC is running the radiation levels on the 'safe' side of the wall are as low as on the surface: we can always access this part of the cavern to intervene if there is a problem, even when there is beam, and we can also use off-the-shelf equipment when technically possible!

4.3 LHCb viewing platform

The main points of interest is the LHCb viewing. It also offers a good opportunity for visitors to take photos! There are two levels in the view platform and the view is not quite the same from them. *In order to allow two groups at the same time you will spend 5 minutes on each platform.*

On the upper level platform you are just about 1 meter above the beam line while on the lower level you are about 1.5 meters below the beam.

You will first go on the upper level platform. In this vantage point you can explain the overall layout of LHCb and there are panels to help you with this with the layout as-is and one event overlaid on a photo of what they are seeing. From right to left you can indicate the interaction point (where protons collide), then the large dipole magnet, the place where the tracking stations sits (now empty), RICH-2, calorimeters and muon detector.

You also have pictures of what the visitor cannot see: the interior of the magnet with the beam pipe and the old trackers and another with the inner part of the calorimeters and muon system and the RICH2 on the right. If fact this last picture was taken in 2013 and it was the first time such a picture could be taken since 2008!

• You can remind people that LHCb in undergoing a major upgrade and many of the detectors have been removed to be replaced by newer 'models'. The readout electronics of all of them, including those still in place, is also being completely replaced. You can find some example in Section 10.

• When pointing out the detectors (or where they should be) you may want to give reference points to identify them. The detectors close to the interaction point, including the VELO with its retractable silicon detectors, the RICH-1 with his gas radiator, and the TT station for tracking cannot be seen: their place is behind the panel with the LHCb logo on the right. They are all being replaced by newer versions and were removed earlier this year. While the new VELO and UT station are under construction and will be installed next year, the RICH-1 frame was modified and some new parts have already been installed. It is now waiting for new mirrors and light detectors. The big blue dipole magnet is clearly visible and will only have some minor maintenance work. On its left there is a big empty space: the Outer Tracker straw detectors with the Inner Tracker just in its center close to beam line were here for over 10 years and the new Scintillating Fiber tracking will soon occupy this space. Following on the left is the RICH-2, hidden behind the metallic stairways with its big volume of gas radiator (its light detectors are also being replaced), the Electromagnetic and Hadronic Calorimeters with their layers of absorbers (lead and iron respectively) and scintillators of which their yellow support structures are clearly visible. At the most left the massive muon system with layers of chambers interspersed within iron shielding walls of which are clearly visible their electronics' towers. The panels on the upper platform can help you in explaining what is and was there.

• After having given the layout of LHCb you can return on the different detectors and pick one where you can go in more details. Some more information is listed later or on the guide of the surface exhibit. If you are an LHCb collaborator working directly on one of the detectors you may want to point that out.

• You will not be able to see the beam pipe either, you can explain that it has been removed at the start of the Long Shutdown (LS2) and it will be reinstalled at the beginning of next year. You may explain how it allows the beams to circulate without the loss of to many protons that would interact with Air molecules. They can see how the beam pipe looks like on the photo on the panel.

• From the viewing platform you can also glance the PX85 shaft. The shaft is 103 metres deep and 10 metres in diameter, and was used to lower parts of the detector down before their final assembly in the cavern. The shaft is also used to lower all the equipment needed for maintenance during the shutdown like the forklifts that may be sitting there on the side. Most of the detectors are brought down in pieces and assembled in situ like big legos. This is the case for most of the detectors, particularly the 'big' one like the Calorimeters. But there are notable exceptions: for example, RICH-2 was lowered down after being completely constructed on the surface, with its mirrors already installed (that moved less then 100 μm during the transport!).

• You can mention that given the shape of LHCb most of the sub-detectors open left and right with respect to the beam line allowing an easy access if it is necessary to intervene on them. In fact most of those remaining are open right now like the ECAL and Muon System! As a curiosity the only one that cannot be open at all in the cavern is RICH-2.

• The particles LHCb is interested in are mostly produced along the beam line, hence the shape of the detector, even though particles are produced in all directions around the collisions points.

• The 'bunker' not only allows to pass on the other side of the detector it also supports the trackers and RICH-2. It is a 'protected' area: low voltage power supplies, gas distribution racks and some electronics is located there because the concrete shields them from particles produced in the collisions.

• On the other side of LHCb, behind grid walls is hosted one of five "cryogenic islands" that distribute the helium coolant and carry kilowatts of refrigeration to the LHC. The one at Point 8 provides the cooling for the LHC magnets that keep the proton on course on both side of LHCb (two sectors each ~ 3.3 kilometers long). The LHC is the largest cryogenic system in the world and one of the coldest places in the Universe. When in operation the LHC magnets are kept at a temperature very close to absolute zero (1.9 K, –271.3°C). Now the magnets have been warmed up to allow working on them to be able to increase the energy of the beam from the 3.5 TeV the LHC operated in 2011 to 6.5 TeV in Run2 and to 7 TeV once the collider will resume operation. The 130 tonnes of helium needed to cool the LHC magnets and to keep the accelerator in the superconducting state are now stored in various points on the surface and 'loaned' to other institutes in the world.

4.4 LHCb Counting Rooms

The visit goes back on the ground inside the visitors' area going out to UX85A passing through the shielding wall and continues along the counting room barracks.

While walking you can explain that:

• In Run1 and Run2 the barracks housed the experiment control's electronics, the data acquisitions and the computer farm of about 1500 PC boxes (each with 12, 16 or 20 CPU-cores) that were used for the online processing of the LHCb data. When a PCs broke it was replaced with a more recent and performing one.

• An average about 40 millions collisions per second took place in LHCb in Run1 and Run2, only a few of them of interest for the physics measurements of the experiment. Dedicated electronics and software running on the PC farm allows selecting those that may be interesting and discard the others, this is what physicists call a trigger. The LHCb trigger reduces by a factor of ~ 10000 the amount of events to write out and we ship them all over the world to reconstruct and analyze (from 40 millions per second to 4000 per second).

4.5 Going back to the surface

You may want to tell people that you are at the end of the tour underground and headed back to the surface, but the tour is not finished! LHCb in undergoing a major upgrade and as they have seen we have removed many detectors. They will now see what we are preparing for the next Run3 to start in 2021. First you will go to the Assembly Hall where they will see new detectors being assembled and then to the new Data Centre we are building to collect and process interesting events.

5. Point 8 Surface Visit

10.1 Back on the surface

Once you exit the PZ elevator back on the surface while walking toward the wardrobe you will pass by a big blue 'cube'. You can mention that under the cover there are huge concrete blocks that were removed from the top of the shielding wall in the cavern to allow removing old cables and pipes and installing new one. They have been sitting there since the very beginning of the Long Shutdown in December of last year and each block will go back it its original position next year.

Don't forget to stop at the locker so that visitors can pick up their bags and put back the helmets once you are on the surface

10.2 Assembly Hall

You will then walk toward the assembly hall. Here is where different parts of sub-detectors build in LHCb collaborating institutes and laboratories or by companies around the world are sent for their final assembly. Once ready and tested they will be lowered via the PX shaft and installed in their final position in the cavern. They will then all undergo a round of commissioning and made to work all together as to provide the 'images' for the physics analysis in Run3.

At the moment the biggest new sub-detector to be installed, the Scintillating Fibre Tracker (a.k.a. SciFi) , is being assembled there: modules are being put on a C-Frame and electronics and services (cooling pipes, cables) are being attached to make fully functional half-stations. A total of 12 C-Frames need to be equipped and installed by mid of next year. The SciFi will be installed downstream of the magnet hence it big size and will replace the Outer and Inner Tracker that have been dismounted in the first months of this year.

Another smaller detector is in his early phase of integration in a 'grey' room in the Assembly Hall, the Upstream Tracker. The frames of the two halves of this sub-detector are in place and dry runs for the installation of the delicate silicon sensors are been carried out.

While you walk toward the assembly all may be a good time to talk about what tracking detector measure (section 10) or some of the physics aim of LHCb (section 9).

In the assembly hall there will be some expert guides that will have more information on the detector, as well as posters to help. You will be able to take a little break from talking but it will now up to you to keep the time. You should spend 10' in the assembly hall.

10.3 The CAST experiment

When you leave the assembly hall you have a little walk to reach the CAST experiment where experts will be there to welcome the visitors and explain what CAST is about. Your main task will be to keep the time and spend 10' at this stop.

During the walk to CAST you can continue discussions on LHCb but you should also mention you are going to see another type of experiment, where beam is not used! CAST (CERN Axion Solar Telescope) is searching for hypothetical particles called "axions". For some theories these particles would explain the subtle differences between matter and anti-matter and would be present in the center of the Sun. CAST uses one of the LHC dipole magnets as the telescope to look for them tracking the Sun, bringing together techniques from particle physics and astronomy.

On the way to CAST on the left there is an old magnet from LEP, you may want to point it out and mention that they will see how different the LHC dipoles are as one of them is used by CAST!

10.4 The data-centre

The data-centre is a state-of-the art installation. Produced by a Dutch-Spanish consortium, it can host more than 10000 server-computers. The total electrical consumption can be up to 3 MW. The figure of merit for data-centre is the fraction of electrical power delivered to the centre, which is actually used by the computers (as opposed to the electrical power used for ventilation, air-conditioning, light, etc.....). The lower the overhead the better. This number is called PUE (Power Usage Efficiency). LHCb's data-centre will achieve a very respectable PUE of less than 1.1, i.e. the overheads are below 10%. Traditional data-centers have between 50 and 100% overheads! This is achieved by so called "indirect" free air-cooling. "Free" means that air from the environment is blown in front of the computers, is sucked in by the computers and then blown out in the rear of the servers. This hotter air is then blown in the environment. All this is done by the big ventilation units of top of the data-centre modules. In summer when the outside air is too hot for the servers (about 30C), the air will be pre-cooled by spraying water in the way of the incoming air. The hot air makes the water evaporate (converts it into steam) and because of this cools down. The same energy-saving principle is employed by the big cooling towers at Point8. Cooling towers are very common also in power-plants, in particular nuclear power-plants, which sometimes leads to the misunderstanding that there would be nuclear power-production at Point8. The data-centre is running 24 hours a day, 365 days a year. When the LHC is not running, the servers are used for producing simulated data-sets or data-processing and analysis. The data-centre consists of 6 modules, the 7th is for the water- and power distribution. During the next 4 years, LHCb will use 4 of the modules and the CERN IT department two.

In case some questions come up:

- What about legionella?

  The water is monitored and treated against Legionella according to French and Swiss environmental legislation).

- Why can't we re-use the waste energy from the servers?

  It is difficult to harvest energy from air, and the only interesting use could be for some heating of some (large) office building very close by. Point8 does not have office-building so there is no good use for the waste-heat.

- Would it be cheaper to run on Amazon. Google, etc…?

  No, because the enormous amount of data produced in LHCb cannot be cost effectively transported over very long distances.

6. Farewell to the visitors

You are at the end of the visit. Unless you need to go back immediately for another group (or you only have a short break) you can finish your discussion with the visitors and ask them if they have questions.

Don't forget to tell them good-bye and wishes them to enjoy the rest of the Open Day in the other visits points!

Once you are done you can accompany them to the exit where the exit gate agents will 'check them out'.

7. LHC accelerator

The general idea at CERN is to use older accelerators as pre-accelerators for the latest accelerators. The newest accelerator called the Large Hadron Collider (LHC) started up at the end of 2009 and has operated continuously (24h for 7 days a week) with few short stops for small maintenance. 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 consists of about ~2500 groups or bunches of about 120 billion protons. The bunches make ~12 000 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. Experiments sees bunches of protons meeting ~30 million times per second. The protons run in separate ring except at the experimental installations where they cross. It takes about ~10 minutes to fill the accelerator and about 20 minutes to be accelerated to their final energy. Then, the beams are maintained colliding for up to ~10-15 hours before the intensity decreased to a value where it is better to refill.

The energy of each proton has been increasing over the year: it started with 3,5 TeV, the it was 4 TeV and eventually it reached 6.5 TeV in 2015 which is actually a few times the kinetic energy of a mosquito (1 mg, 0.1 m/s ~ 10^{-8} J ~ $3*10^9$ eV). As a comparison: 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, but carried by 10^{15} protons which weighs all together ~10^{-9} grams. (1 g of hydrogen, essentially protons, has $6*10^{23}$ protons).

The transversal size of the beams at nominal energy at the interaction point is about 17 μm (RMS) in ATLAS and CMS (~ 40 μm in LHCb), and the longitudinal length is about 5 cm (RMS).

Whereas the luminosity at the LHCb collision point is tuned to limit the number of proton interactions between one and two, ATLAS and CMS see up to 100 pairs of protons interacting per bunch crossing, that is 3 billion interactions per second…

The whole accelerator, 36000 tonnes, is cooled down to 1.9 K which makes it the "coolest" object in the Universe (Cosmic Microwave Background radiation at 2.7 K). Initially 12 million litres of liquid nitrogen is 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 is not a perfect circle. It is made of eight arcs and eight 'insertions' (IP). The arcs contain the dipole 'bending' magnets, while the insertion have straight sections few hundred metres long. The experiments sit in the middle of long straight sections like the one you are in.

• In an accelerator, particles circulate in a vacuum tube and are manipulated using electromagnetic devices: dipole magnets keep the particles in their nearly circular orbits, quadrupole magnets focus the beam, and accelerating cavities (Radio Frequency) are electromagnetic resonators that accelerate particles and then keep them at a constant energy by compensating for energy losses. The Radio Frequency is in Point4 one of the other Open Days visit points.

• Insertion quadrupoles like those where the view point is, are special magnets used to focus the beam down to the smallest possible size at the collision points, thereby maximizing the chance of two protons smashing head-on into each other. The transverse size of the beam in LHCb is ~ 0.04 millimetres, as thin as human hair and is even smaller in ATLAS and CMS.

• The most numerous magnets in the LHC are the dipoles of which there are 1323. They represented the most important technological challenge for the LHC design. In a proton accelerator, like the LHC the maximum energy that the beam can reach is directly proportional to the strength of the dipole field (given a specific acceleration circumference). At the LHC the dipole magnets are superconducting and able to provide the very high field of 8.3 T over their length what could not be achieved with 'warm' magnets. In 2021, the LHC will also install two magnets which will reach a high field of ~11 T, in view of a future possible major upgrade of the accelerator.

8. Experiments at the LHC

The LHC experimental facility consist of the older CERN accelerator complex, the LHC accelerator and four main experiments ATLAS, ALICE, CMS and LHCb.

The ATLAS and the CMS detectors are so called general-purpose detectors aimed at discoveries, by directly producing new particles, such as the Higgs boson, Supersymmetric partners, and other 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 slightly different method.

The ALICE experiment is an experiment dedicated to the study of lead ion collisions. A state of matter called quark-gluon plasma 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 have seen hints of this new state of matter but ALICE is set out to investigate this carefully. Colliding lead ions 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. This in fact occurs also in proton-Ion collisions and in 2012 and early this year collisions of this type where collected by ALICE and the other LHC experiments.

LHCb is also a special purpose experiment dedicated to beauty and charm particle search for new physics in CP violation and rare decays. The LHCb physicists hope to indirectly see new particles (or even discover them) by their effect on the properties measured of the beauty and charm particles because they could be produced in "loops", i.e. a virtual production due to the quantum mechanical uncertainty principle. LHCb was initially designed to make precision measurements with B mesons (mesons containing b-quarks), but it is doing much more that it was designed for, not only probing all type of hadrons that contain the b-quark, but also doing very precise measurements of charm particles (hadrons containing the c-quark). The very special shape of the LHCb detector also allows to probe particle production mechanisms is an area not covered by the other three big LHC experiments.

9. LHCb's physics aims

• Matter is made up of atoms, with nuclei surrounded by electrons – example of a fundamental particle (without visible substructure).

• Nuclei are made up of protons and neutrons that were initially thought to be fundamental particles.

• We now know that protons and neutron have internal structures and are make of fundamental particles, called quarks. Six types of quark exist, given exotic names: up, down, charm, strange, top and bottom (or beauty). It is the last of these that LHCb has been designed to study, hence the b in the name, LHCb in fact stands for Large Hadron Collider beauty experiment, in other words the experiment to study beauty at the LHC.

• Quarks are always coupled with an anti-quark or in triplets with two other quarks, so they cannot be observed directly but through particles that contains them. Particle made of quarks are referred to as hadrons.

• Protons and neutrons are made of only of two type of quarks, the up and down. Particles with other type of quarks can only be found in cosmic rays or produced in experiments.

• Two type of exotic hadrons, pentaquarks, were observed for the first time ever by LHCb with data collected in Run1. The experiment confirmed them and observed a third one with the more copious data collected in Run2. Pentaquarks are particle made of five quarks and although the possibility they could exist was included in the quark model when it was initially proposed in 1964 it took 50 years before their existence was demonstrated experimentally.

• In the Standard Model, particles have antiparticles (same mass, opposite charge) When particles meets their antiparticles, they annihilate to give photons. It is expected that matter and antimatter equally produced at the beginning of the Universe, but that most annihilated. However, some matter was left over and it is responsible for world we live in. Imbalance between matter and antimatter requires breaking the symmetry between them, known as CP violation: a combined operation of C = charge conjugation (swapping particles for antiparticles) and P = parity (spatial inversion, like reflection in a mirror)

• Particles that contain the b-quark exhibit this CP violation, so are a good place to study it.

• About 100,000 such particles were produced every second in LHCb until 2018, far more than ever produced before, so we can be selective and study the interesting ones. In Run 3 the number of b particle produced will increase by a factor of 5 allowing not only more precise measurements but also to look for effects that occur even less frequently.

9.1 Cosmological perspective

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.

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 antiquarks, and force-carrying particles called bosons and energy carried by photons.

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.

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.

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.

After about a billion years, the first stars were born in an otherwise dark Universe. Galaxies formed, and the Universe continued to expand. 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.

In the 1960s 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 (for the kaon system). In technical terms this is called CP violation. Calculations indicate, however, the observed level of this is not sufficient to account for the observed matter-antimatter asymmetry in our Universe.

The full explanation for this imperfect symmetry looks like it requires new physics that could be revealed by studying 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 and for which CP violation occurs more frequently.

10. The LHCb detector

About a thousand billion pairs of anti-beauty and beauty quarks are produced in LHCb per year, and we select a few tens of million of their decays to study carefully off-line using computers to reconstruct the events that were recorded. By measuring their properties extremely precisely we detect asymmetries between particles and antiparticles, that should 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 subdetectors, 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 subdetector is also very big in order to make precise measurements of the extremely fast and energetic particles that are produced.

Tracking - The topology of the particle reaction is recorded using tracking detectors. LHCb has four trackers: Vertex Locator (VELO), Silicon Tracker (ST), Outer Tracker (OT) and muon detector until 2018; Vertex Locator (VELO), Upstream Tracker (UT), Scintillating Fiber Tracker (FT) and muon detector from 2021.

Momentum - The momentum of each charged particle is obtained by measuring the curvature of the particle trajectory, as recorded by the tracking detectors combined with the magnetic field of the spectrometer dipole.

Energy - The energy of particles is measured using calorimeters. The LHCb calorimeter system consisted of a PreShower (PS) and a Scintillator Pad Detector (SPD) followed by an Electromagnetic Calorimeter (ECAL) and a Hadron Calorimeter (HCAL) until 2018. From 2021 onward only the ECAL and HCAL will be present.

Particle Identification - The particles are identified by the signatures they leave in different type of detectors. The LHCb particle identification is based on two Ring

Imaging Cherenkov detectors (RICH-1 and -2), the calorimeters and the muon detector.

10.1 Vertex Locator (VELO)

Until 2018

The VELO tracks the particles close to the collision with a precision of ~10μm 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 1 cm before decaying (1.5 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 0.3 mm thick silicon detectors (21) measuring the particle trajectories in cylindrical coordinates (r, ϕ, z) and has 22000 signal cables which carry data from some 200 000 sensor channels. The sensitive area of the silicon plates starts at about 8 mm 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 few proton-proton interactions are recorded by vetoing high multiple interaction crossing in the first level trigger (L0).

From 2021

To be added…

10.2 Silicon Tracker (ST)

Until 2018

The Silicon Tracker consists of a Trigger Tracker (TT) and an Inner Tracker (IT). The TT is based on silicon microstrip detectors of about 100μm pitch, covering a large area of a few square metres arranged in layers of ~ 1 square metre each. It has the task of tracking low-momentum particles that 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 transverse momentum to be estimated for tracks with large-impact parameters, quickly enough for the information to be used early in the trigger decision (although this is not used in the current version of our trigger selections, it was the original motivation for the name of TT).

The three stations of IT are also based on similar silicon microstrip detectors and they have the task of tracking particles that travel close to the beam line. Although only covering about 2% of the area of the OT, about 20% of tracks pass through the IT, due to the higher density of tracks close to the beam pipe.

10.3 Upstream Tracker (UT)

From 2021

To be added…

10.4 Outer Tracker (OT)

Until 2018

Together with the Silicon Tracker, the Outer Tracker forms 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 that produce Cherenkov light in the RICH detectors, 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 +/- 5o with respect to vertical. Each detector module consist of 5 mm straw tube drift chambers, in two layers which are staggered with respect to each other and which are packed into a gas-tight box.

10.5 Scintillating Fibre Tracker (SciFi or FT)

From 2021

To be added…

10.6 Magnet

Despite the fact that the LHCb magnet is a conventional warm magnet and not superconducting, 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 precision asymmetry measurements.

The magnet contains two coils, each weighing 27 tons, mounted inside a 1450-tonne steel yoke. Each coil is 7.5 m long, 4.6 m wide and 2.5 m high, made of a pure aluminium conductor which is 50 x 50 mm^2. The conductors have a 24mm bore to circulate cooling water through the entire magnet.

10.7 Ring Imaging Cherenkov detectors (RICH 1 and 2)

The RICH detectors 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 of the cone depends on the velocity of the particles. Focusing mirrors reflect the Cherenkov photons onto position-sensitive photon detectors. The cone is reflected in a circle such that the angle can be known by measuring the radius of the circle hence the name of the detector Ring Imaging Cherenkov, in short RICH. Knowing the trajectory and momentum of the particle (via the trackers and the magnetic field) 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 a detection area of 3 m^2.

Until 2018

The photon detector were Hybrid Photon Detectors, HPDs, that were specially developed for LHCb. They were circular leaving some insensitive area between then when arrange on the detection plane.

From 2021

The photon detectors are Multi Anode Photo Multiplier Tubes, MaPMT. They have a square cross section reducing the inefficient area between them when in their final arrangement. The mirrors of RICH1 are also changed as they are arranged with a slightly different optics.

10.8 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 x 12 x 41 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) Wave-Length Shifting 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, and is proportional to the energy of the incoming electrons, positron or photon.

The HCAL principally identifies and measures energy of particles containing quarks, i.e. hadrons (HCAL = Hadron CALorimeter). It consists of tile structure of iron and 3 mm 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 that summed up is proportional to the initial incoming hadron.

The scintillation induced by the particles is also readout via Wave-Length Shifting fibres. In total the HCAL has 80 km of fibre and weighs ~500 tonnes.

Until 2018

The electromagnetic calorimeter was preceded by a Scintillator Pad Detector (SPD) and a Pre-Shower (PS) detector. The SPD and the PS signaled the presence of charged particles. They have been removed and from 2021 the discrimination of charged particles connected to calorimeter signals will rely on the tracking system.

10.9 Muon Detector

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 x 6 m^2 (M1) to 12 x 10 m^2 (M5). The total number of wires in the chambers is about 2.5*106, 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.

In between each muon station there is a muon filter consisting of iron blocks. The muon filter serves to attenuate hadrons behind the calorimeters that can lead to muon misidentification. Muons interacting very little with matter are not stopped by these iron walls. The total weight of the muon filter is 2100 tonnes.

10.10 Trigger and data acquisition

Until 2018

The LHCb detector registers particle collisions at a rate of 40 million per second. The readout system used to be made of two levels of triggers to reject uninteresting events. The first level trigger decision (L0) had a latency of 4 μs meaning that 160 events have to be stored while waiting for the decisions to arrive. The trigger decisions were based on information from the Pile-up system, the calorimeters and the muon chambers. The trigger was implemented in hardware (L0 trigger processors and L0 decision unit) and selects events from about 1/40 of the bunch crossings, i.e. the accept rate is 1 MHz. The full detector is then read out.

The remainder of the trigger is known as the High Level Trigger, which is a software trigger that runs on the online processing farm and will reduce the data rate to 5 kHz which are sent to storage. This data-rate includes events suitable for calibration of the detector. The rate for our physics analyses is 4 kHz. The data acquisition system is able to cope with a data rate of 12 Gbytes/s – equivalent to 17 CDs per second.

From 2021

In 2021, after a two years upgrade, the LHCb experiment will resume operation without the first level hardware trigger. All events – at 40 MHz – will be passed to the software High Level Trigger in order to improve the selection efficiency. This will result in a ~40

Tb/s readout network, using some of the most advanced and recent network technologies present on the market. In effect it will be the "biggest" / "fastest" (technically speaking "highest bandwidth") scientific data acquisition system built to date.

The data will be sent from the detector underground to a new data-centre on the surface of Point8 via more than 18000 fibres, which are approximately 300 m long. Within the data-centre the data will be distributed using the latest network technology using hundreds of 100 Gigabit / s links – (a single 100 Gbit/s link can carry more than 1.5 Million simultaneous phone-conversations!)

11. LHCb general facts

• LHCb measures rare processes with extremely high precision, Discrepancies from what the Standard Model predicts will give us hints of what physicists call "New Physics" leading to a more complete theory

• The 'b' in the name stands for the b-quark. The name was chosen when it was designed to indicate that its initial purpose was to make measurement at the LHC of particles containing the b-quark. While the experiment is now doing much more than that the name remains.

• Many physics results have already been produced with the data collected in the past 10 years, about 490 physics papers have been published as of September 2019 and many more are on the way.

• The LHCb collaboration in September 2019 consists of 1338 members from 79 institutes in 18 countries. Of these are 343 are PhD students, 233 women and 907 are author of the physics papers.

• The detector covers a "forward" region from ~ 1° to 17° from the beam line, because most b hadrons are produced in that forward cone

• B hadrons are detected from the way they decay to give other particles, which leave tracks in the detectors (or energy deposits in the calorimeters)

• The typical b-hadron lifetime ~ 10^{-12} s (1 millionth of a millionth of a second) but at close to speed of light this corresponds to ~ 1 cm in LHCb, so that tracks from decay don't point exactly at the b-hadron production point

• B-hadrons are quite heavy, so decay products have high transverse momentum (i.e. a kick in the direction transverse to the beam line)

• Characteristic particles are produced in the decay of b and c-hadrons, e.g. electrons, muons, kaons

• The sub-detectors are designed to detect these different aspects of b decays. The complete detector is 20 m long, 10 m high, 12 m wide and weighs 5600 tonnes.

• The channel count ranges from few thousand individual elements (HCAL) to 500,000 (RICH), read out electronically a million times a second.

• The Trigger system selects interesting events for writing to storage at 10 kHz by making a fast study of a limited part of the detector.

• Event size ~ 50 kbytes × 10^{10} events per year → million GB/year of data would require a stack of CDs ~ a kilometer high (for Run1 and Run2)

• Computing power for trigger was provided by a farm of ~1500 commercial computers, each with 12, 16 or 20 CPU-cores (for Run1 and Run2)

• Data analyzed by physicists around the world using the Grid of interlinked data-centres

• Cavern length 70 m

• Cavern maximum width 20 m

• Height 18.60 m

• The LHCb detector cost is 75 million CHF (~ 15% of general-purpose detectors). Upgrade cost additional approx.. 55 million CHF, excluding cost for the data-centre.

12. LHC general facts

• The name stands for Large Hadron Collider: it collides beams of protons which are members of the class of particles called hadrons (from the greek *adros* meaning *bulky*). Hadrons are made of quarks.

• The LHC is the largest scientific instrument in the world, the highest energy accelerator and the largest cryogenic system

• Ring 27 km in circumference, 9600 magnets

• Cooled using liquid helium to 1.9 K (-271°C), colder than outer space

• The whole cooling process of a sector takes a few weeks. The refrigeration process happens in three phases: first the magnets are cooled down to 4.5 K (-268.7°C), then the magnet cold masses are filled with liquid helium and finally the magnets are cooled at superfluid helium temperature to 1.9 K (-271.3°C). The first phase happens in two steps: first the helium is cooled to 80 K in the refrigerators' heat exchangers by using about 10000 tons of liquid nitrogen. Then refrigerator turbines bring the helium temperature down to 4.5 K (-268.7°C), ready for injection into the magnets' cold masses.

• The choice of the operating temperature for the LHC has as much to do with the 'super' properties of helium as with those of the superconducting niobium-titanium alloy in the magnet coils. Among many remarkable properties, superfluid helium has a very high thermal conductivity, which makes it the coolant of choice for the refrigeration and stabilization of large superconducting systems

• Large variety of magnets including dipoles, quadrupoles, sextupoles, octupoles, decapoles, etc. giving a total of about 9300 magnets. Each type of magnet contributes to optimizing a particle's trajectory.

• The LHC dipoles use superconducting niobium-titanium (NbTi) cables, which become superconducting below a temperature of 10 K (–263.2°C), that is, they conduct electricity without resistance. In fact, the LHC operates at the still lower temperature of 1.9 K (–271.3°C), which is even lower than the temperature of outer space (2.7 K or –270.5°C).

• A current of 11700 A will flow in the dipoles, to create the high magnetic field of 8.3 T, required to bend the 7 TeV beams around the 27-km ring of the LHC. For comparison, the total maximum current for an average family house is about 100 A.

• Accelerates protons, particles found in all ordinary matter (the nucleus of hydrogen atom) to 99.999999% of speed of light

• Beams of protons pass in both directions around ring, inside pipes at very high vacuum: 10^{-13} × atmospheric pressure.

• Collide at a four points around the ring, at which experiments are sited to look at results of p-p collisions

• Collisions between bunches of protons will occur at 40 million times a second. In 2011 and 2012 they did at 20 million, although some tests were done at 40 million times a second.

• Energy of proton beams = 4 TeV in 2012 = 4 $\times 10^{12}$ eV. Energy 1eV given to a proton by 1 V potential difference so equivalent to 4 million million volts acceleration, achieved using radio frequency cavities. Has been 6.5 TeV for most of Run2. Will rise to 7 TeV in the future.

• Total power ~ 120 MW when running. Reduced by use of superconducting magnets, most power used for cooling

• Collisions had energy of 7 TeV in 2011 and 8 TeV in 2012, the highest ever achieved. In every-day units ~ 1 mJ, but concentrated into tiny volume → can create new Particles. They will eventually occur at an energy of 14 TeV.

• In particular, Higgs-like boson was observed last year = last missing piece predicted by the Standard Model: best theory we have of particle physics, which describes well ~ all measurement made until now.

• We hope to also find other new particles, which will lead us to a more complete theory: for example, explaining the "Dark Matter" seen in astrophysics

• We also measure rare processes with extremely high precision, for example in the LHCb experiment. Discrepancies from what the Standard Model predicts will give us hints of what physicists call "New Physics" leading to a more complete theory.