Introduction

In order to succeed in the BL4S competition it is not necessary to propose a very ambitious experiment. It may be better to start with a simple question. Then ask yourself if this question can be answered with the material we will provide (see below) or with material that you could add. As you are refining your proposal, you will learn a lot about particle physics, detectors, data acquisition, data analysis, statistics and much more. You will not be alone during this learning process. There is a list of volunteer physicists who are happy to interact with you and to provide you with additional information and advice.

There are two types of set-ups for experiments with elementary particles: collider and fixed target configurations. The Beamline for Schools (BL4S) experiment is of the fixed target type.

In a collider (such as the LHC) particles are entering a detector from opposite directions, collide and release their energy. This energy then gets transformed into new particles. Usually, these primary particles are not stable (A Higgs boson, for example, decays after 10^{-22} s into other, secondary particles that can be seen in the detector).

The BL4S experiment will take place in a beamline at the CERN Proton Synchrotron (PS). The particles entering the experimental area have a well-defined momentum between 0.5 and 10.0 GeV/c, as defined by the user. For comparison, the maximum energy of the proton beams at LHC is 6500 GeV/c. In high energy physics, the units for energy, momentum and mass are GeV, GeV/c and GeV/c^2, resp., where c is the speed of light. In the world of particles, these units are more practical than the MKS units: 1 GeV = 1.6×10^{-10} Joule, 1 GeV/c^2 = 1.783×10^{-27} kg. Time is usually measured in ns = 10^{-9} s which is the time it takes for light to move 30 cm.

The beam particles are of different types: electrons or protons which are stable, but also short-lived particles like pions or kaons that are created when the primary beam from the PS hits the target. Since the pions and kaons decay to muons along the beamline, there is also a background of muons in the experimental area.

Background information: The particles that we provide for your experiment are relativistic. This means they are moving with almost the speed of light. As an example, the mass of a pion is 0.140 GeV/c^2 and the velocity of a pion with momentum of 3 GeV/c therefore is equal to 0.99891*c (this can be computed from the relativistic formula for momentum). The energy of a pion is 3.0032 GeV ≈ the momentum.

Because of the acceleration cycle of the PS, the particles arrive in bursts: about 10^6 particles during 0.4 s every 10 s.

In a typical experiment, a target is placed in the beam. The properties of the particles resulting from the interaction between the beam particles and the target can be measured and allow us to try to understand the physics of the interaction. To measure the incoming and outgoing particles, commonly used elements are:

- Cherenkov detectors for particle identification of beam particles
- Scintillation detectors that record the passage of a charged particle
- Tracking chambers that measure the position of a charged particle traversing the chamber.
- Magnet: if the track of a particle is measured before and after a bending magnet, its momentum can be calculated
- Electromagnetic calorimeters that allow to measure the energy of electrons and photons

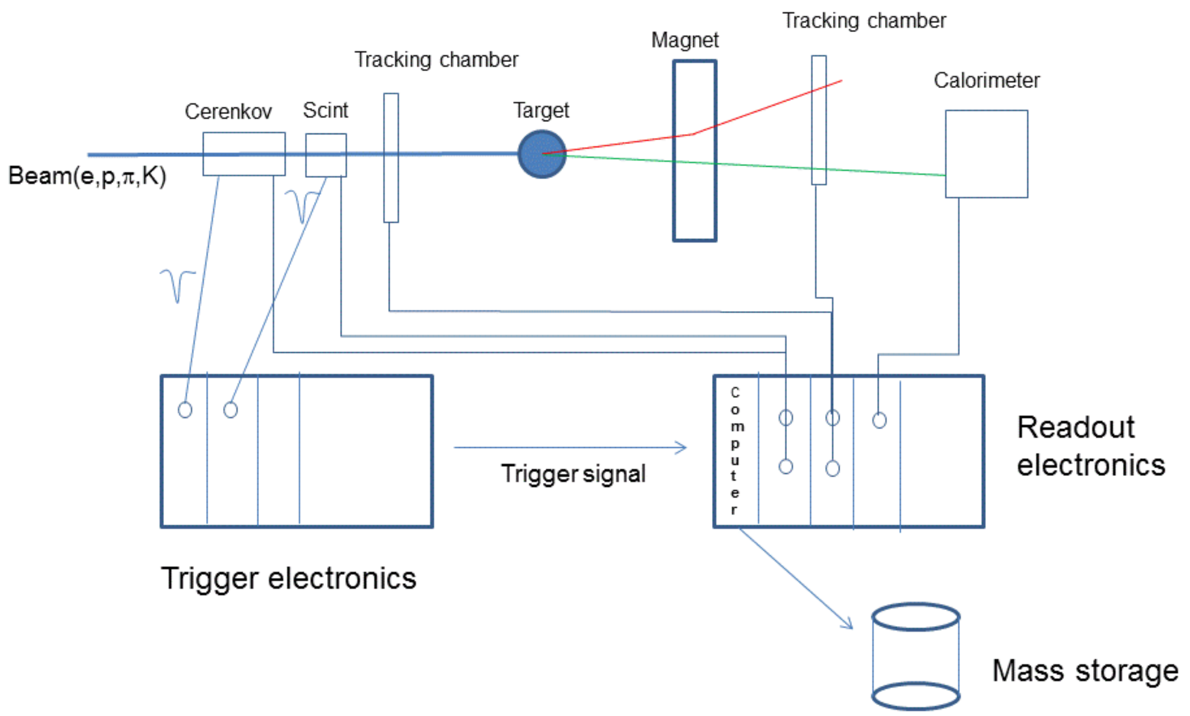
In the BL4S experiment, examples of these detectors are made available as described in more detail in the following chapters. It should be emphasized that experiments are quite possible without making use of (all) of these detectors.

The detectors in the list above are *electronic* detectors: when a particle interacts with the detector, an (analogue) electrical signal is produced in different ways. In a Cherenkov or scintillation detector, light is emitted and converted into an electrical pulse using a photomultiplier. In a gaseous tracking chamber, ionization generates electrons that are multiplied in electric fields. The typical duration of the signals is 100 ns and voltages about 100 mV to 1 V. The signals are sent to a readout system where they are digitized and eventually readout by a computer.
Signals from some of the detectors are used to build a *trigger*. The trigger identifies interesting interactions ("events") and instructs the computer to initiate the readout of the data from all the detectors. The trigger is a fundamental and complex component of LHC experiments where collision rates are very high and only a very small fraction of the collisions are of interest. For example, the production of a Higgs boson occurs in an event out of 10^{12}.
In BL4S the trigger is simpler and might consist in requiring coincident signals from two scintillator counters to indicate that a charged (beam) particle went through the target.

When a trigger occurs, data from all detectors are recorded by the readout system and a signal is sent to a computer that transfers the data to mass storage, usually a disk. This mechanism is very similar to when you take a picture with a digital camera. When the shutter-release button is pressed, data (light) is transferred to the CCD and recorded to memory. One difference is that in the case of BL4S, the exposure time is about 100 ns.

As one can imagine, a large amount of software has been developed at CERN and elsewhere for the analysis of experimental data. A data analysis framework called Root is used by many physics laboratories all over the world.

To summarize the introduction, the figure below shows schematically an example of a BL4S experiment including the trigger and readout system. Again, the figure shows an experiment where most of the instrumentation provided by CERN is used, but simpler set-ups are also possible. In a separate document, you will find a list of examples of experiments.



(Figure 1)

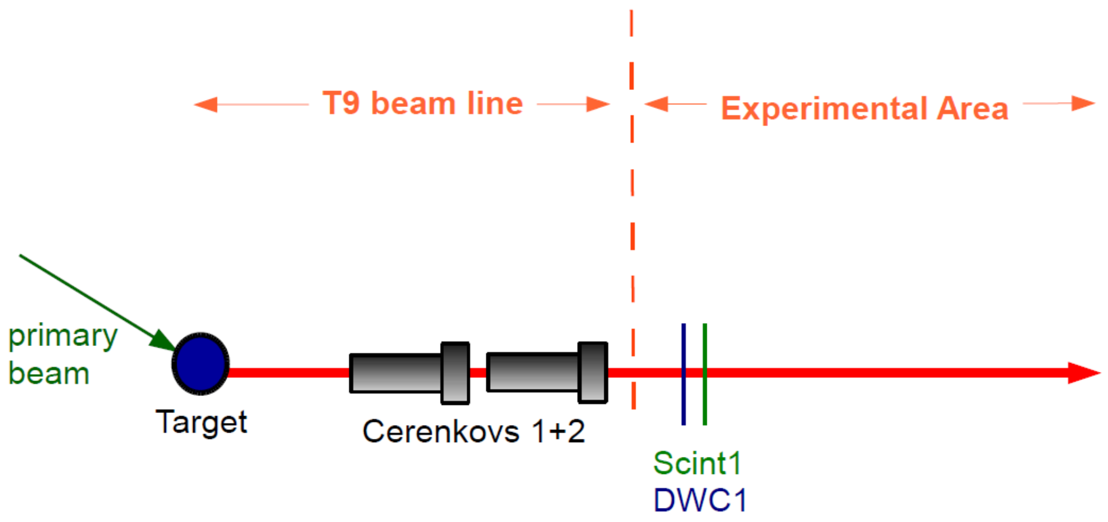
Information about the T9 beam line and experimental facilities

The BL4S experiment will take place at the PS accelerator.

The incoming proton beam from the PS accelerator impinges on the North target and thus produces the particles for the T9 beam line. The collisions of the protons with the target will provide a variety of particles, such as electrons, positrons, muons, pions, kaons and (anti-)protons. The T9 beam line, used for the experiment is therefore a mixed hadron and electron beam and can transport either positively or negatively charged particles with momenta between 0.5 GeV and 10 GeV. The beam is delivered uniformly in time over a burst of 0.4 seconds. Depending on scheduling, such a burst is provided typically once or twice per 15 seconds. The maximum particle rate per burst of 10^6 is achieved for a 10 GeV/c positive beam, but drops for lower energies. For negative beams the rates are typically lower, meaning the bursts contain fewer particles. The beam travels approximately 55 m before it enters the experimental area.

The experiment will take place in an area of about 5 m by 12 m, containing a number of detectors, which are fixed, along with devices that can be changed or added. They are used to measure and analyse the properties of the beam and its composition. All available apparatus are listed in this document. Additionally it is possible to install devices that are brought by your team in the experimental area. However please note that CERN cannot guarantee the installation of the suggested devices. Each request has to be reviewed individually. The installation of combustible material (e.g. wood) is not possible for safety reasons. It is also not possible to expose any biological material to the beam.

The fixed setup of the beam line
(for explanations, see below)



Target

The primary beam, coming from the PS accelerator impinges on a target before it enters the area of the T9 secondary beam. There are different target heads available, allowing different electron components of the beam. The core of the target is always light material (aluminum or beryllium). In some targets a tungsten plate enhances the electron content of the beam.

Beam Composition

Depending on the target and energy, the beam is a mix of different kinds of particles. The figures 2 and 3 below show the composition of the positive (Figure 2) and negative (Figure 3) beam.

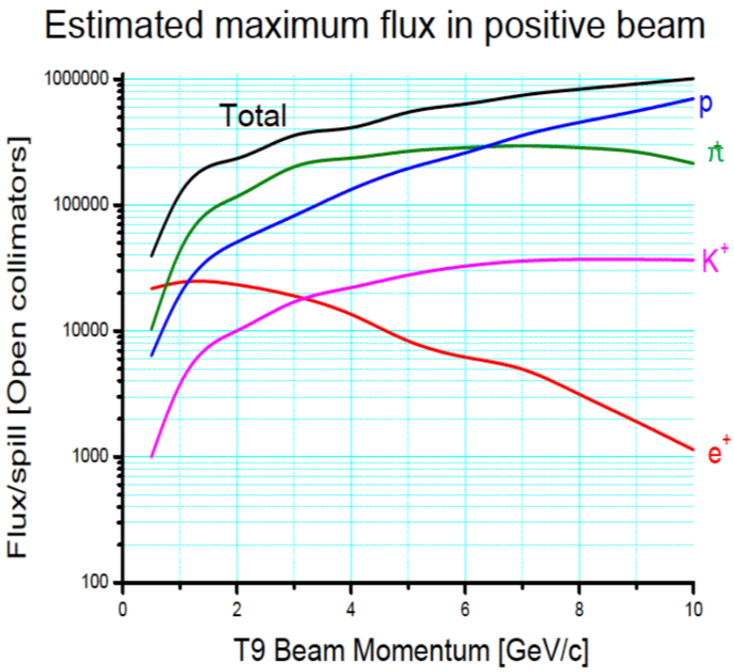


Figure 2: Positive beam

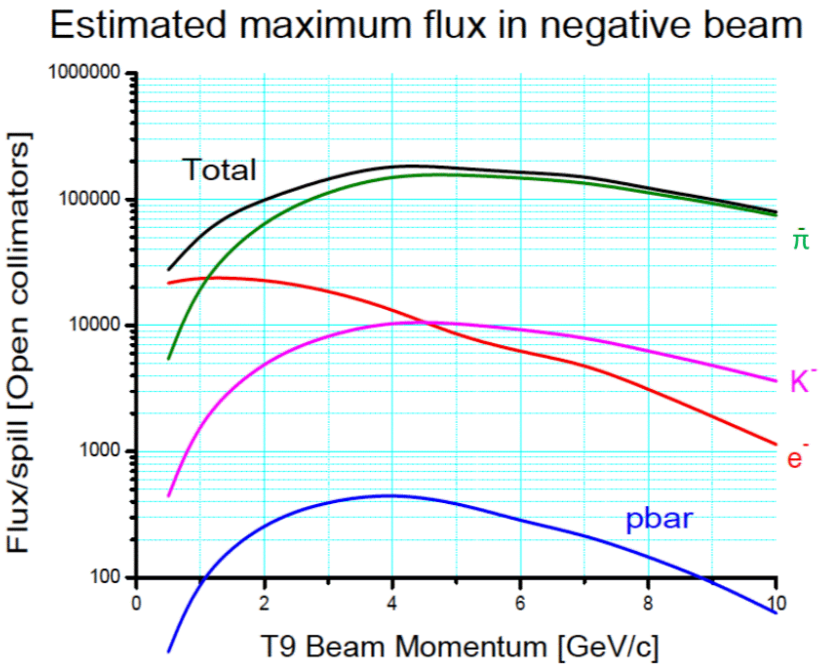


Figure 3: Negative beam

As this may look complicated, here is an example:

If the T9 beam is set up to deliver a negative beam with an Energy of 4 GeV, each burst (spill) of 400 ms duration will deliver ~300 anti-protons (pbar), ~10.000 electrons and kaons as well as ~100.000 pions.
See also: http://gatignon.web.cern.ch/gatignon/T9flux.pdf

Beam shape
The beam has a more or less round cross section. In the focal plane the beam spot has a diameter of about 2 cm. The further away from the focal plane, the bigger the diameter.

Beam background
In addition to the particles created by the interaction of the proton beam with the target there is a background of other particles in T9. Some of the pions of the secondary beam for example decay into muons. Other particles may get created by collisions of the beam with the air in the experimental zone. All of these "undesired" particles are called background. Depending on the experiment that you are going to propose this background can mask the effect that you are looking for. Understanding the background is essential to almost every experiment we do at CERN. Please contact us if you need additional information.

Bending magnets

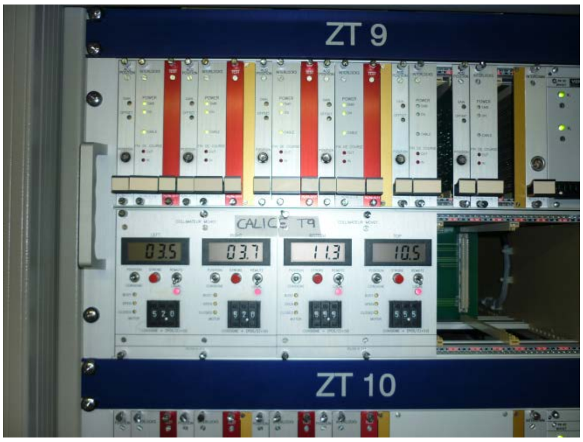
Bending magnets are used in the beam line not only to guide the particles in a certain direction but also to choose the particles' energies (between 0.5 GeV and 10 GeV) by defining the magnet currents accordingly. A bending magnet is a dipole with a vertical orientation of the magnetic field. The particles that cross these field will be deflected horizontally.

Quadrupole magnets

Quadrupole magnets are used to control the beam size and to focus or defocus the particles in the beam line. Their role is similar to the role of lenses in your camera. However, contrary to an optical lens, a quadrupole will focus the beam in one plane, but defocus the beam in the other plane. That means a horizontally focussing quadrupole defocusses vertically and vice versa. These magnets are used to set the focus of the beam to a defined place in the experimental area.

Collimator

A collimator is a tool to filter the beam of particles. There are two collimators in the T9 beam line. The horizontal collimator changes the width of the momentum distribution of the beam depending on its opening. Thus it rejects particles that have either a higher or lower momentum than a pre-determined range. The vertical collimator, on the other hand, filters particles according to their initial angle on leaving the target. Any particle with a larger angle than selected is rejected.



Scintillator (Scint)

A scintillation detector consists of a scintillator slab connected to a sensitive photomultiplier. Scintillation is the light produced when charged particles pass through certain materials, such as certain plastics with specific additives. The scintillation light can be detected by photomultipliers. The photomultiplier tube transforms the incoming light emitted by the scintillator into an electrical signal and amplifies it. One scintillator counter is part of the fixed setup of the beam line. Four additional scintillators are readily available for installation in the experiment. You can for example measure the time it takes to a particle to travel from one scintillator to another or simply count the arriving particles.

Delay Wire Chamber / Tracking chamber (DWC)

This tracking device is an evolution of the multi-wire proportional chamber (MWPC), developed at CERN by Georges Charpak. Where the MWPC detects the position of a charged particle by indicating which wire was closest to the particle position, the delay wire chamber improves the position resolution by also measuring the time between the particle passage and delay of the chamber signal which is measured via a delay line. The delay measures the distance between the particle and the wire. The dimensions are 10x10cm^2 and the position resolutions of 100 to 200 µm can be achieved. However, the chamber can only measure one particle inside a certain time window. One DWC is part of the fixed setup of the beam line. Two additional DWCs can easily be installed for the experiment, if required.

Cherenkov detector

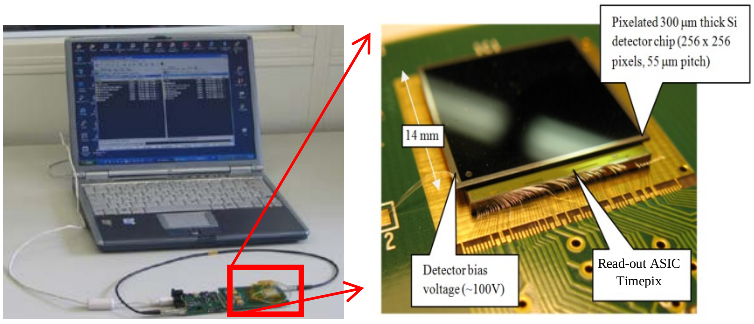
Nothing is faster than the speed of light in vacuum. However in other media, such as certain gasses, the velocity of particles can exceed the velocity of light in that medium. If that's the case, the particles emit so called Cherenkov light. By adjusting the pressure of the gas, the velocity threshold of the particles emitting Cherenkov light can be chosen. Since the momentum of all traversing particles is preselected, the different velocities can be assigned to different particle masses and thus different types of particles. Electrons will in practice always emit light in any gas, contrary to the other particles. Depending on the choice of gas, in a given energy range, a discrimination between electrons, pions and heavier particles (mostly kaons or protons) may be possible.

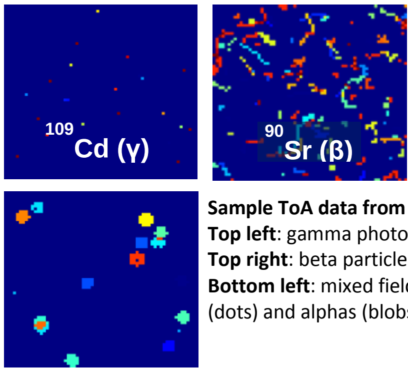
Two Cherenkov detectors are part of the fixed setup, each consisting of a Cherenkov threshold selector and a photomultiplier. Additional to the pressure of the gas, you can choose between certain gasses like carbon dioxide, helium, argon and nitrogen, according to what particles you would like to detect. If you choose not to use the Cherenkov counter in your experiment, it will remain on the beam but can be emptied, so that it won't interfere with the properties of the beam.

Optional additional devices

Timepix detector

Timepix is a hybrid pixel detector developed by the Medipix2 Collaboration. It contains 65,000 square pixels of 55 µm pitch, with a 300 µm thick silicon diode sensor that detects ionising radiation. The chip can deliver up to 1000 frames per second. Timepix can be operated in time-over-threshold (ToT) mode to measure the energy of detected particles, or time-of-arrival (ToA) mode to distinguish between particles and/or reconstruct tracks of particles. Certain charged particle species can also be identified by the morphology and energy of their interaction with the sensor.



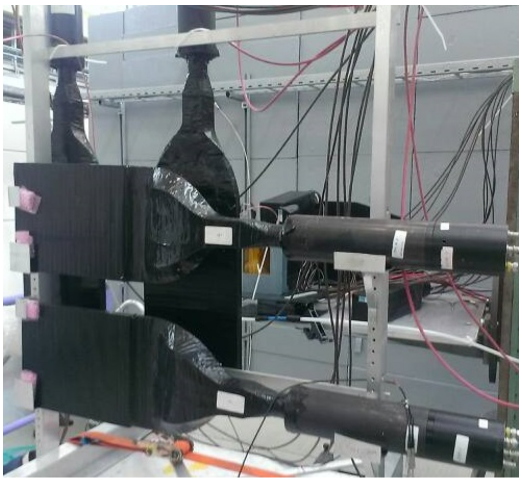


Sample ToA data from Timepix
Top left: gamma photons (dots)
Top right: beta particles (squiggles)
Bottom left: mixed field of gammas (dots) and alphas (blobs)

Lead Crystal Calorimeter

A calorimeter is a detector that measures the energies and positions of impinging particles. An electron hitting the calorimeter for example will produce a fully contained electromagnetic shower, thus depositing all its energy in the calorimeter and therefore allowing a very precise measurement of its energy. Although heavier particles produce a signal as well, the energy deposition is smaller than for electrons. By measuring the deposited energy, signals induced by electrons can be distinguished from those induced by muons, hadrons (pions, kaons and protons), with a certain amount of overlap. Although sometimes used as a position detector, the determination of a particle's position is less precise. The calorimeters are 10x10x37cm^3 in dimensions, and 16 of them are available.

Halo counter



The halo counter is a set of 4 scintillator counters that form a hole around the beam passage. Its purpose is to identify particles that are too far away from the beam axis. While a collimator filters the beam by rejecting particles with a larger angle immediately, the halo counter identifies them and thus makes it possible to choose to either reject them or flag them. That's useful e.g. for flagging particles, that interacted with a certain absorber and underwent scattering. The opening of the BL4S Halo Counter can be adjusted between 1 cm and 15 cm.

Absorbers

An absorber is a plate of material that absorbs a fraction of the particles in the beam or degrades the momentum of particles of a specific type. Typical absorber materials are lead or tungsten, but other lighter materials can also be used (e.g. polyethylene). By using a lead absorber, electrons will lose a large amount of their energy in the lead whereas most of the hadrons cross the absorber essentially unobstructed. The electrons that have interacted with the absorber can then be flagged with a halo counter (see above).

Muon Filter

A muon filter is a special absorber in the form of a massive iron block. It will be installed by crane if needed. All particles of the beam travelling through the iron are absorbed completely, except for the muons. By installing a detector such as a scintillator counter behind the muon filter, the muon content of the beam can be detected.

MNP17 Magnet

CERN's large, polarity-changeable, horizontal dipole magnet has a maximum field of 0.96 T over a length of 52 cm. The gap height is 30 cm and the useful aperture width is 1 m. The field can be varied by adjusting the current. This magnet can be installed inside the experimental area on request in order to determine the momentum of the particles.

Data acquisition

We will provide a complete data acquisition system for reading out the detectors and controlling the experiment. This system is fast enough to trace up to 2000 particles per second.

The data acquisition system provides tools for the on-line monitoring of the experiment. For this purpose the data will be visualized in the form of histograms. In addition, a 3D tool will be available in order to look at selected events. This 3D event viewer is provided by National Instruments. You can create an account and download it freely at https://decibel.ni.com/content/docs/DOC-41129. The S/W comes with a free LabView licences as well as some selected events from the 2014 BL4S experiment. Don't hesitate to try it out in order to get an impression of how it works and how a BL4S detector set-up may look like.

Glossary

North target	The target that serves the T9 beamline (CERN jargon)
PS, CERN Proton Synchrotron	The PS is an accelerator with a circumference of 628 m. It is used to accelerate (mainly) protons. https://en.wikipedia.org/wiki/Proton_Synchrotron
Positron	This is the anti-matter twin of the electron. https://en.wikipedia.org/wiki/Positron
Muon	Like an electron but more heavy and not stable (decays into other particles) https://en.wikipedia.org/wiki/Muon
Pion	A hadron made from a quark and an anti-quark https://en.wikipedia.org/wiki/Pion
Kaon	A hadron made from a quark and an anti-quark https://en.wikipedia.org/wiki/Kaon
(Anti-)proton	A hadron made from three quarks (or anti-quarks) https://en.wikipedia.org/wiki/Proton
Hadron	A particle made from quarks https://en.wikipedia.org/wiki/Hadron
GeV	A measure for energy used in particle physics https://en.wikipedia.org/wiki/Electronvolt
Root	A powerful software framework for the display and analysis of physics data https://root.cern.ch/documentation
Burst	A spill of particles from an accelerator
Biological material	Living cells, human / animal tissue
Secondary beam	Particles created from the interaction of a beam with a target
Target head	The material at which the primary proton beam is directed. The choice of material influences the composition of the secondary beam
Electron content	The relative number of electrons in a secondary beam
Scintillator	A transparent material that emits light when it gets penetrated by charges particles https://en.wikipedia.org/wiki/Scintillation_counter
Cherenkov detector	A gas volume that emits light when it gets penetrated by charges particles. The light emission depends on the type of particle and its momentum https://en.wikipedia.org/wiki/Cherenkov_detector

Photomultiplier	A device that converts photons into electric signals https://en.wikipedia.org/wiki/Photomultiplier
Tracking	The measurement of the trajectory of a particle
Pixel detector	A tracking detector with a 2-dimensional array of sensors. Usually made from Silicon.
Electromagnetic shower	An avalanche of particles created from the interaction of high-energetic particle with the material of a calorimeter.
Collider	An accelerator that collides two beams that are cruising in opposite directions.
Boson	https://en.wikipedia.org/wiki/Boson
Calorimeter	A detector that measures the energy of a particle