Introduction

It is not necessary to propose a very ambitious experiment in order to succeed in the Beamline for Schools (BL4S) competition.
It may be better to start with a simple question. Then, ask yourself if this question could be answered with the material that 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-up for experiments with elementary particles: collider and fixed target configurations. In a collider (such as the Large Hadron Collider (LHC)), particles are entering a detector from opposite directions, collide and release their energy. This energy then gets transformed into new particles. In a fixed-target experiment, a charged particle such as an electron or a proton is accelerated by an electric field and collides with a target, which can be a solid, liquid, or gas. Also, in this collision, new particles can be created by the energy release.

Short overview of BL4S

The BL4S experiment is of the fixed target type. A very simplified explanation of the experimental setup goes like this: Fast moving protons from the Proton Synchrotron will first hit a target called the "North target" or "Production target", creating many different particles. The proportions of these particles depend on the adjustable momentum of the primary protons, as shown in figures 2 and 3. This stream of particles is now called the secondary beam. You can decide whether the secondary beam should contain entirely positively (figure 2) or negatively charged (figure 3) particles. Your experiment will now be a setup of target(s), devices and detectors using the particles from this secondary beam. A list of possible detectors and devices are at your disposal and their applications are given in the table below; these will be explained more in depth later.

Detector	Measurement
Calorimeter	Energy of particles
Cherenkov detector	Particle type and momentum
Scintillator detector	Passage detector
Tracking detector	Tracks the trajectory
Device	**Application**
Collimator (vertical)	Filters particles according to their initial angle on leaving the target
Collimator (horizontal)	Changes the width of the momentum distribution
Bending magnet	Changes direction of particles
Quadrupole magnet	Focuses the particle stream in one plane, defocuses it in the other

In-depth overview of BL4S

The BL4S experiment will take place in a beamline (called T9) at CERN's 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. In comparison, the maximum energy of the proton beams at the LHC is 6500 GeV/c. In high-energy physics, the units for energy, momentum and mass are GeV, GeV/c and GeV/c^2, respectively, 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 nanoseconds (ns), where 1 ns = 10^{-9} s, which is the time it takes for light to move a distance of 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 production target. Since the pions and kaons decay to muons along the beamline, there is also a background of muons in the experimental area.

You might consider watching a short introductory video about hadrons, which **includes mesons, pions and kaons.**

The particles that we provide for your experiment are relativistic. This means they are moving at almost the speed of light. As an example, the rest mass of a pion is 0.140 GeV/c^2 and, with a momentum of 3 GeV/c, it will therefore have a velocity equal to 0.99891×c (this can be computed from the relativistic formula for the momentum). The energy of a pion is 3.0032 GeV, so the kinetic energy is much larger than the rest energy of the pion.

Because of the acceleration cycle of the PS, the particles arrive in bursts: about one million (10^6) particles in a 0.4 second burst, at a rate of one or two bursts per minute.

In a typical experiment, a target is placed in the beam. The properties of the particles that result from the interaction between the beam particles and the target can be measured, allowing you to try to understand the physics of the interaction. Alternatively, you can study the particles of the secondary beam itself; for example, by observing the decay of the unstable particles. To measure the incoming and outgoing particles, commonly used elements are:

- Cherenkov detectors for particle identification
- Scintillation detectors that record the passage of a charged particle
- Tracking chambers that measure the position of a charged particle
- Electromagnetic calorimeters that allow the measurement of electron, positron and photon energies
- Magnets: if the track of a particle is measured before and after a bending magnet, its momentum can be calculated

Examples of detectors in the BL4S experiment are described in more detail in the following chapters. It should be emphasized that experiments can be conducted 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 the signal voltages are typically 100 mV to 1 V. The signals are sent to a readout system where they are digitized and eventually read out by a computer and stored to disk.
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 one out of a trillion events (where one trillion is 10^{12}).
In BL4S, the trigger is much simpler and might, for example, require 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 charge coupled device (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.

The experimental area

Example of an experimental setup

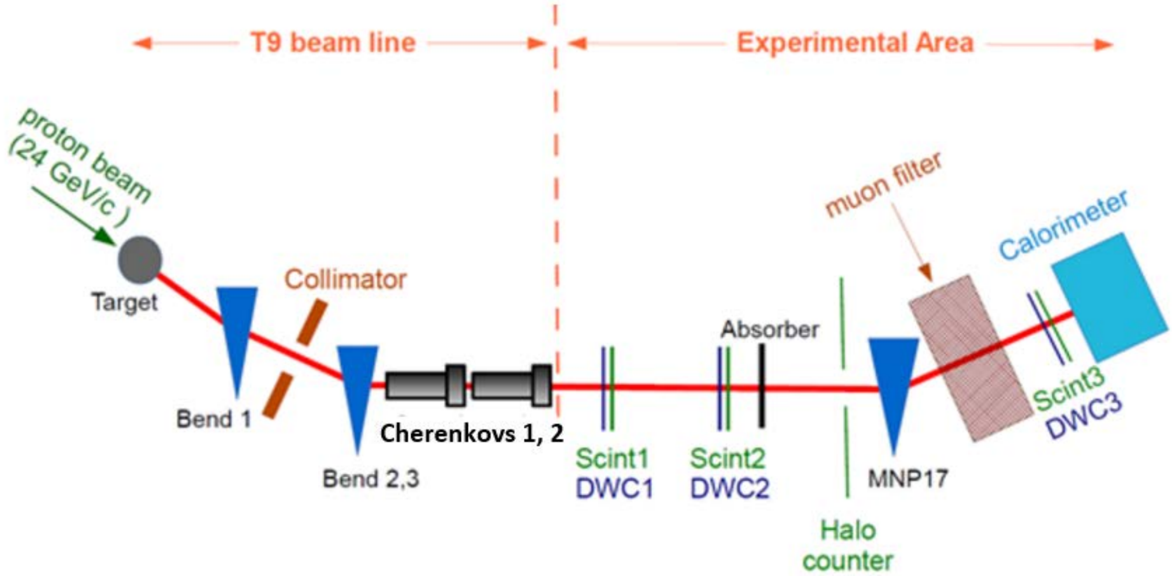


Figure 1. The proton beam from the proton synchrotron enters from the left and hits the production target. The text gives detailed information about the various points along the beam-path.

1. The proton beam from the PS accelerator enters with a momentum of 24 GeV/c.
2. The beam hits the production target, which can be made of aluminium or beryllium. In some targets there's a tungsten plate. The particle content of the beam depends on the material in the target.
3. Magnets at each of the three bends and at the collimator are all setup to filter the particle beam so only particles a momentum between 0.5 GeV/c and 10 Gev/c can pass.
4. Then, the particle beam goes through the Cherenkov detectors that allow a first particle identification. Depending on the choice of gas in the Cherenkov detectors, it may be possible to discriminate between electrons, pions and muons.

5. The beam enters the experimental area where there are two scintillators (Scint1 and Scint2). The scintillators count the number of particles and it is possible to measure the time it takes for a particle to travel from one scintillator to the other.
6. There are also two Delay Wire Chambers (DWC) that measure the positions of the particles.
7. In this example setup, there is a lead absorber in the beam-path. The lead absorbs electrons, but, essentially, the heavy particles will go through without interacting with the lead atoms.
8. The MNP17 is a strong magnet that bends the charged particles. The momentum of the particles can be determined from the tracks.
9. The muon filter is a huge, iron block that stops all particles, except muons and neutrinos. The Scint3 scintillator will then count the number of muons that pass through.

Additional information about the experimental facilities

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 to 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 large amounts 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.

Information about the beamline

The beam is delivered uniformly in time, over a 0.4 second burst. Depending on scheduling, such a burst is provided typically once or twice a minute. The maximum particle rate per burst of 10^6 is achieved for a 10 GeV/c positive beam, but drops for lower momenta. 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.

Beam composition

The beam is a mixture of different kinds of particles that depend on the target, the energy or the momentum. Figures 2 and 3 below show the composition of the positive (Figure 2) and negative (Figure 3) beam.

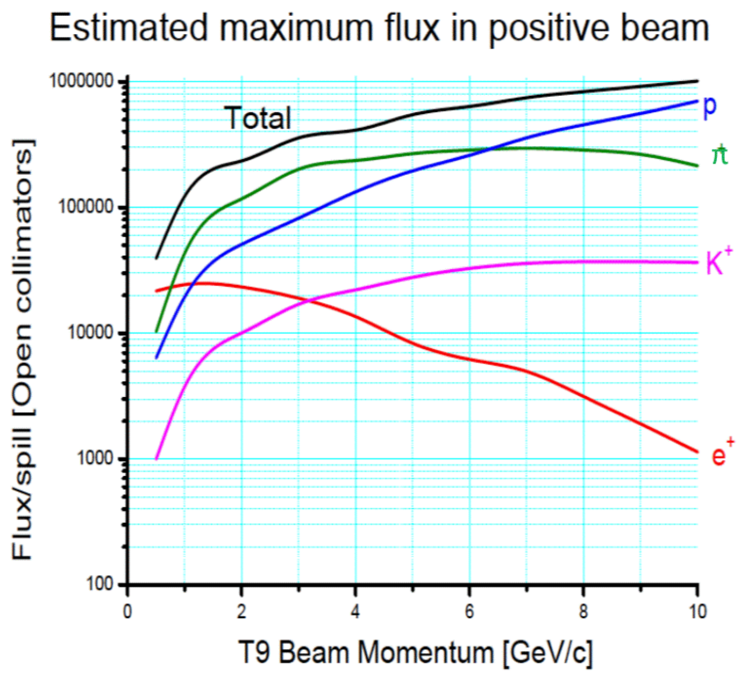


Figure 2: Positive beam which consists of positively charged particles. Flux/spill means the number of particles per spill, or equivalent, per burst. There are no muons present at this stage, but they appear when positive pions or kaons decay.

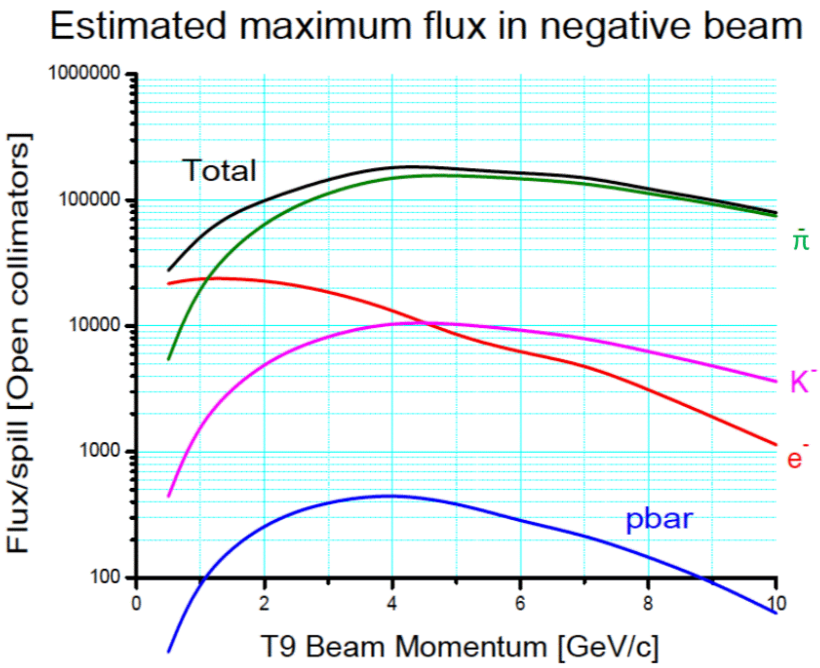


Figure 3: The negative beam consists of negatively charged particles. The pbar graph describes the antiprotons, which have the opposite electrical charge of a proton. There are no muons present at this stage, but they appear when negative pions or kaons decay.

Here is an example:

If the beam is set up to deliver a negative beam with a momentum of 4 GeV/c, each burst (spill) of 400 ms duration will deliver ~450 antiprotons (pbar), ~10.000 electrons and kaons, as well as ~150.000 pions.
See also: http://gatignon.web.cern.ch/gatignon/T9flux.pdf

Beam shape

The beam has, more or less, a round cross section. In the focal plane, the beam spot has a diameter of about 2 cm. The further away the beam is from the focal plane, the larger the diameter. The position of the focal point can be adjusted.

Beam background

In addition to the particles created by the interaction of the proton beam with the production target, there is a background of other particles in the beamline (T9). Some of the pions of the secondary beam, for example, decay into muons. Other particles may be 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.

Information about the usable devices

Bending magnets

Bending magnets are used in the beamline 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 vertically-orientated magnetic field. The particles that cross the field will be deflected horizontally.

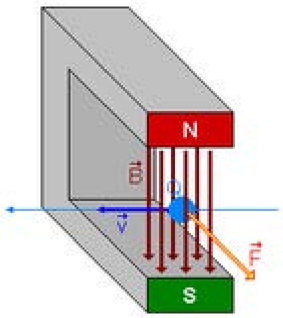


Figure 4: A dipole magnet with the vertical magnetic field and a charged particle moving horizontally into the field. The force is perpendicular to the magnetic field vector and the velocity vector, deflecting the charged particle horizontally.

Image source: https://hr.wikipedia.org/wiki/Portal:Fizika/Slika/37,_2007.

Quadrupole magnets

Quadrupole magnets are used to control the beam size and to focus or defocus the particles in the beamline. 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. This means that a horizontally focussing quadrupole defocuses vertically and vice versa. These magnets are used to set the focus of the beam to a defined place in the experimental area. Figure 5 shows how the proton beams are squeezed in the LHC:

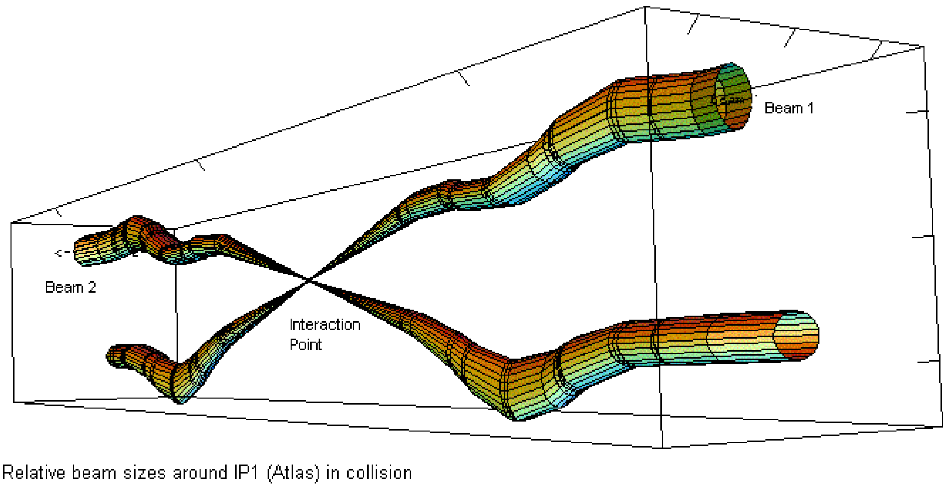


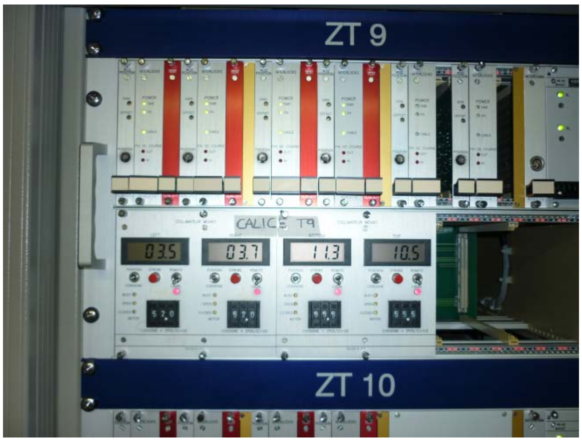
Figure 5. The proton beams in the LHC are squeezed (made thinner) by quadrupole magnets, in order to increase the collision rate.

Image source: http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/collisions.htm

You might consider watching this short instructional video, which shows how charged particles move when influenced by a magnetic field: Particle movement in a magnetic field.

Collimator

A collimator is a tool used to filter the beam of particles. There are two collimators in the T9 beamline. 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 [scintillator] is a material that produces scintillation light – a property of luminescence – when excited by ionizing radiation. Luminescent materials, when struck by an incoming particle, absorb the particle's energy and scintillate, i.e., re-emit the absorbed energy in the form of light. A scintillation detector or scintillation counter is obtained when a scintillator slab is connected to an electronic light sensor, in our case a sensitive photomultiplier tube. Photomultiplier tubes absorb the light emitted by the scintillator and re-emit it in the form of electrons, via the photoelectric effect. The subsequent multiplication of these photoelectrons results in an amplified, electrical pulse that can then be analysed; yielding meaningful information about the particle that originally struck the scintillator.

One scintillation counter is part of the fixed setup of the beam line. Four additional scintillators are available for installation in the experiment. Some examples for the use of scintillation detectors are measuring the time it takes for a particle to travel from one scintillator to another, or simply counting the arriving particles.

You can watch a simple animation here:

https://upload.wikimedia.org/wikipedia/commons/2/22/Scintillation_Detector.gif

Delay Wire Chamber (DWC) / Tracking chamber

A **multi-wire proportional chamber (MWPC)** is a type of proportional counter that detects charged particles and can give positional information on their trajectories by tracking the trails of gaseous ionization. The multi-wire chamber uses an array of wires at high voltage (anode), which run through a chamber with conductive walls held at ground potential (cathode). Alternatively, the wires may be at ground potential and the cathode may be held at a high negative voltage; the important thing is that a uniform electric field draws the extra electrons or negative ions to the anode wires with little lateral motion. The chamber is filled with a carefully chosen gas, for example, a mixture of argon and methane, such that any ionizing particle that passes through the tube will ionize surrounding gaseous atoms. The resulting ions and electrons are accelerated by the electric field across the chamber, causing a localized cascade of ionization. This collects on the nearest wire and results in a charge proportional to the ionization effect of the detected particle. By computing the pulses from all of the wires, the particle's trajectory can be found.

The **Delay wire chamber** is a further development of the MWPC. While the MWPC detects the position of a charged particle by indicating which wire was closest to the particle's position, the delay wire chamber improves the position resolution by also measuring the time between the particle passage and the 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 position resolutions of 100 to 200 µm can be achieved. The unit "µm" represents a micrometre, one millionth of a metre. However, the chamber can measure only one particle inside a certain time window (100 ns approximately). One DWC is part of the fixed setup of the beamline. Two additional DWCs can easily be installed for the experiment, if required.

Multi Gap Resistive Plate Chamber (MRPC)

Our two MRPC detectors have a surface area of 30 x 30 cm. They provide, like the DWCs, tracking information but with a smaller resolution. Their main advantage is that they can provide very accurate time information for the passage of a particle. In a well-calibrated system, values as low as 100 ps (where ps stands for pico second, one trillionth of a second) can be reached. Therefore, the MRPCs are very useful detectors for time-of-flight measurements.

The MRPC consists of a stack of resistive plates, where spacers between these plates define a series of gas gaps. Anode and cathode electrodes are placed on the outer surfaces of the outermost resistive plates while all interior plates are left electrically floating. The two basic principles of the MRPC are:

1. The resistive plates are transparent to the fast signals generated by the avalanches inside each gas gap. The induced signal on the external electrodes is the *sum* of the activities of *all the gaps*.
2. The internal resistive plates are all electrically floating. Initially, they take the correct voltage due to electrostatics but are kept at this voltage because of the flow of electrons and positive ions created by the avalanches in the gaps.

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 is the case, the particles emit so-called Cherenkov light or radiation. Cherenkov radiation is emitted by a charged particle when it passes through a material with a speed greater than c/n, where n is the index of refraction of the material and c is the speed of light. The angle of the photons with respect to the charged particle direction depends on its velocity. By adjusting the pressure of the gas, the velocity threshold of the particles that emit Cherenkov light can be chosen. Since the momenta of all traversing particles are preselected, the different velocities can be assigned to different particle masses and, thus, different types of particles. Therefore, one could compute the mass of the particle by its momentum and velocity, hence identifying the particle. Electrons will, in practice, always emit light in any gas, unlike the other particles. Depending on the choice of gas, in a given energy range, a discrimination between electrons, muons and pions is possible. Identifying heavier particles (kaons or protons) is not possible for technical reasons.
Two Cherenkov detectors are part of the fixed setup, each consisting of a Cherenkov threshold selector and a photomultiplier. In addition to the pressure of the gas, you can choose between certain gases 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.

You might want to see these two instructional videos explaining Cherenkov light:
Particle physics and Cherenkov light
Cherenkov light: What is it?

Optional additional devices

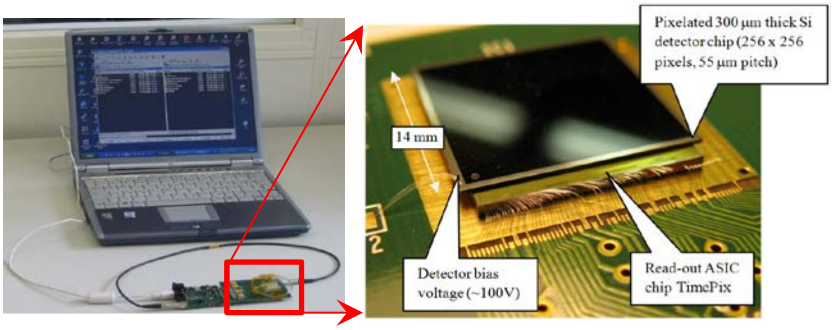
Timepix detector

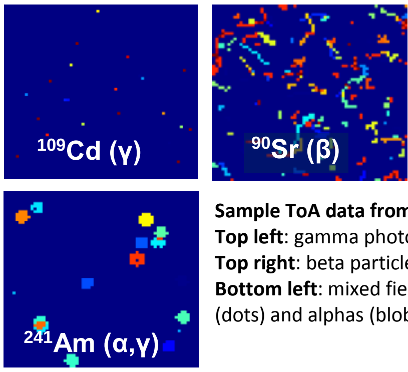
The Timepix chip is designed as a universal readout chip for various types of radiation. It can be used in combination with a pixelated semiconductor detector with a gaseous Time Projection Chamber (TPC) or without any sensor (electrostatically collecting electrons).
See also these videos:
Medipix 2 - See Through Science
Material resolving CT using Timepix

The hybrid silicon pixel device Timepix was developed at CERN by the Medipix collaboration, with support of the EUDET project. It is based on its successful predecessor Medipix2. The device consists of a semiconductor detector chip (usually containing a 300 µm thick piece of silicon) bump-bonded to a readout chip. The detector chip is equipped with a single common backside electrode and a front side matrix of electrodes (256 x 256 square pixels with a pitch of 55 µm). Each element of the matrix (pixel) is connected to its respective preamplifier, discriminator and digital counter integrated on the readout chip. The noise of the analogue circuitry is about 650 electrons. Each Timepix pixel can work in one of three modes:

1. Medipix mode – The counter counts the incoming particles
2. Timepix mode or ToA (Time of arrival mode) – The counter works as a timer, measuring time of the particle detection. This mode distinguishes between particles and/or reconstruct tracks of particles
3. Time over threshold (TOT) mode – The counter is used as Wilkinson type ADC, allowing direct energy measurement in each pixel (this mode measures the energy of the detected particles)

Each individual pixel of the Timepix device in TOT mode is connected to its own analogue circuitry and AD converter. Thus, the device contains 65536 independent ADCs. All of them have to be individually calibrated.





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)

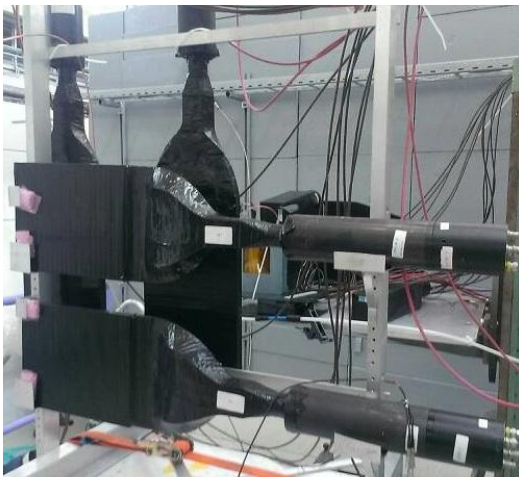
The timepix pixel detector: This device consists of two chips connected by the bump-bonding technique. The upper chip is a pixelated semiconductor detector (usually silicon). The bottom chip is ASIC readout containing a matrix of 256 x 256 preamplifiers, comparators and counters. The chip can deliver up to 1000 frames per second.

Lead Crystal Calorimeter

A calorimeter is a detector that measures the energy of impinging particles (although it is not a tracking detector). 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 and hadrons (here: 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 than in usual tracking detectors. The 16 available calorimeters each have a volume of 10x10x37cm^3.

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 immediately filters the beam by rejecting particles with a larger angle, the halo counter identifies them and thus makes it possible to choose to either reject or flag them. This is 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 unhindered. The electrons that have interacted with the absorber can then be flagged with a halo counter (see above). Most absorbers are interlaced with the detector itself and not used as a separate apparatus.

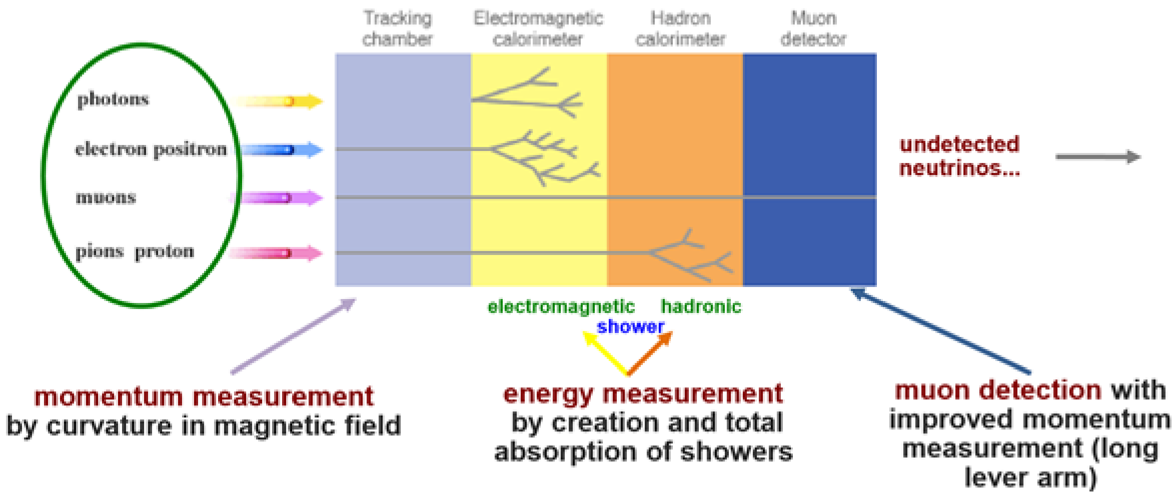
The image shows the steel absorber used in the calorimeter of the ATLAS experiment

Muon filter

Muons are charged particles that like electrons and positrons but are 200 times heavier. Unlike most of the particles, they are not stopped by calorimeters because muons can penetrate several metres of iron without interacting, Therefore, chambers to detect muons are placed at the very edge of the experiment, where they are the only particles likely to leave a signal.

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 that travel through that 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.

EM shower in the calorimeter



See also this interactive animation of particles' passage through different detector parts:
Interactive animation of the ATLAS detector

MNP17 magnet

CERN's large, polarity-changeable, horizontal dipole magnet has a maximum field of 0.96 Tesla over a length of 52 cm. The gap height is 30 cm and the useful aperture width is 1 m. By adjusting the current, the field can be varied. 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 here. The S/W comes with a free LabView licence as well as some selected events from the 2014 BL4S experiment. BL4S Event Software Display can be used on both Windows and Linux platforms. When you enter the link, you will find the installation instruction, LabVIEW source code, download source and tutorial. Don't hesitate to try it out in order to get an impression of how it works and what a BL4S detector setup may look like.

Glossary

Antiproton	A hadron made from three anti-quarks, also written as pbar:
Biological material	Living cells, human / animal tissue
Boson	Particles can be categorized as bosons or fermions according to their intrinsic spin
Calorimeter	A detector that measures the energy of a particle
Cherenkov detector	A gas volume that emits light when it gets penetrated by charged particles. The light emission depends on the type of particle and its momentum
Collider	An accelerator that collides two beams which are cruising in opposite directions as in the LHC
Electromagnetic shower	An avalanche of particles created from the interaction of a high-energetic particle with the material of a calorimeter
Electronvolt	A unit of energy used in particle physics
GeV/c	A unit of momentum used in particle physics
GeV/c^2	A unit of mass used in particle physics
Hadron	A particle made up from quarks
Kaon, K^0, K^+,K^-	A hadron made up from a quark and an anti-quark
MKS units	Units expressed in meters, kilograms and seconds
Muon, μ	A particle like an electron but much heavier and not stable (decays into other particles)
North target	The target head that serves the T9 beamline (CERN jargon)
Pbar	Another name for an antiproton
Photomultiplier	A device that converts photons into electric signals
Pion, π^0, π^+, π^-	A hadron made from a quark and an anti-quark
Pixel detector	A tracking detector with a 2-dimensional array of sensors; usually made from silicon

Positron, e^+	A particle that is the antimatter twin of the electron.
Production target	Same as North target, target that protons first collide with
PS, CERN Proton Synchrotron	The Proton Synchrotron is an accelerator with a circumference of 628 m. It is used to accelerate (mainly) protons, giving the primary beam of protons.
Root	A powerful software framework for the display and analysis of physics data.
Scintillation counter	A transparent material that emits light when penetrated by charges particles.
Secondary beam	Particles created from the interaction of the primary beam with the target head
T9 beamline	The beamline before the experimental area
Target head	The material at which the primary proton beam is directed; the choice of material influences the composition of the secondary beam
Tracking	The measurement of the trajectory of a particle