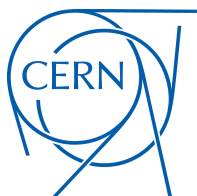




Beam and detectors

Beamline for Schools 2022

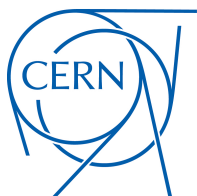


Preface

All the big discoveries in science have started by curious minds asking simple questions triggered by the observation of natural phenomena: How? Why? This is how you should start. Then you should investigate, with the help of this document, whether your question could be answered with the available equipment (or with material that you can provide) and the pool of detectors of Beamline for Schools. As your proposal takes shape, you will be learning a lot about particle physics, detectors, data acquisition, data analysis, statistics and much more. You will not be alone during this journey: there is a list of [volunteer physicists](#) who are happy to interact with you and to provide you with additional information and advice.

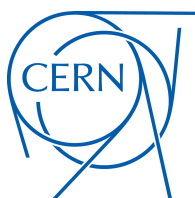
Remember: It is not necessary to propose a very ambitious experiment to succeed in the Beamline for Schools competition. We are looking for exciting and original ideas!

Note: At the beginning of this document you will find a glossary that provides you with short explanations of the scientific terms and jargon that we are using in text. For more detailed information we recommend you to start with a search in Internet, Wikipedia is usually a good starting point. It usually provides very accurate and detailed information about scientific terms and you may find explanations in your mother tongue.



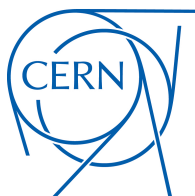
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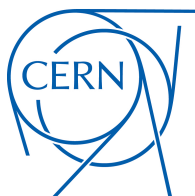


Glossary

Anti-protons	An antiproton, also known as $p\bar{}$, is the antimatter twin of a proton. Hence it is a hadron made of the three anti-quarks: anti-up, anti-up and anti-down. 14
Beam divergence	The spreading of the particles in the beam along their path. 13
Beam halo	The cloud of particles surrounding the main beam in an accelerator. 13
Biological material	Living cells, human / animal tissue, bacteria, viruses. 16
Boson	Particles can be categorized as bosons or fermions according to their intrinsic spin. Bosons have integer spin numbers, and fermions fractional spin numbers. 11
Calorimeter	A detector that measures the energy of a particle. 9, 21
Cherenkov detector	A detector based on a medium that emits light when it is crossed by charged particles. The light emission depends on the type of particle and its velocity. Wikipedia: Cherenkov detector . 9, 13
Collider	An accelerator that collides two beams which are travelling in opposite directions as in the LHC. 8
Electromagnetic shower	An avalanche of particles created from the interaction of a high-energetic particle with the material of a calorimeter. This process is defined "an avalanche" because the particles are produced both from the primary interaction of the beam with the material and from further interactions of the collision products. 21



Flux	Quantity that provides the number of particles crossing a defined surface (for example the opening of a collimator) in a fixed amount of time. The dimensions are typically an absolute number over the square of a length per time: $[\text{Number}]/[\text{L}^2 \cdot \text{T}]$. 14–16
GeV, Electronvolt	Units of energy used in particle physics. An eV is defined as the energy acquired by an electron accelerated by a potential difference of 1 V: $1 \text{ GeV} = 1.6 \times 10^{-10} \text{ Joule}$. The letters G stays for Giga, $1 \text{ GeV} = 1 \times 10^9 \text{ eV}$. 12
GeV/c	A unit of momentum used in particle physics. 12
GeV/c²	A unit of mass used in particle physics. $1 \text{ GeV}/c^2 = 1.783 \times 10^{-27} \text{ kg}$. 12
Ionizing particle	A particle with enough energy to knock out electrons of atoms or molecules. 17
Kaons	Kaons are hadrons, heavier than pions, and made of quarks of type up, down or strange. Kaons can be positively, negatively charged or neutral, and within a characteristic time, they transform into other particles, typically pions. 14
MicroMegas	Micro-MESh Gaseous Structure, a particle detector that enhances the signal from particle ionization in a gas volume. MicroMegas are used to record the tracks of particles. See also: Wikipedia: MicroMegas . 18
MKS units	Units expressed in meters, kilograms and seconds. 12



Momentum

Product of the mass of a particle and its velocity. For a relativistic particle (speed close to that of light) one should consider the increase in the particle mass defined by the Lorentz factor: γ : $\mathbf{p} = m \cdot \gamma \cdot \mathbf{v}$, where m is the particle mass, γ the Lorentz factor defined as $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ and \mathbf{v} the speed vector. 9, 12, 15, 16

Momentum acceptance

Distribution of particle momenta that will be accepted and registered by a detector. For example, one could set a minimum momentum value, and only particles with a momentum above this threshold will be considered. 13

Muons

A muon, μ , is a particle similar to an electron but much heavier and not stable (it transforms into other particles within a characteristic time). 14

Photomultiplier

A device that converts photons into electric signals. 9, 17

Pions

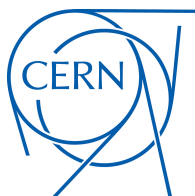
Pions, π , are particles made of quarks, hence they are hadrons. More precisely, they are made of one quark and one antiquark of type up or down. Depending on the constituents, a pion can be positively, negatively charged or neutral, π^+ , π^- , π^0 , respectively. A pion is not a stable particle but within a certain time, it transforms into something else, typically muon/antimuon and a neutrino/antineutrino. 14

Positron, e^+

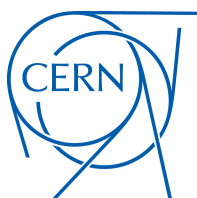
An elementary particle that is the antimatter twin of the negatively charged electron; this means both have the same properties, but the positron is positively charged. 14

Proton

A proton is a subatomic particle, with a positive electric charge. 12



Root	A powerful software framework for the display and analysis of physics data. 11
Scattering	An interaction between two particles that changes the particle's energy and momentum. Depending on the properties of the scattering process, this leads to the generation of new particles (inelastic scattering), or simply to a deflection and energy loss for the initial particle (elastic, or multiple scattering). 17
Scintillation counter	A transparent material that emits light when penetrated by charged particles. 9, 17
time-of-flight measurements	Measurements that provide information about the time taken by a particle to travel a certain distance. They provide information about the momentum of the particle. 20
Tracking	The measurement of the trajectory of a particle. 9, 21
Trigger	It identifies interesting interactions ("events") and instructs the computer to initiate the read-out of the data from all the detectors. 10



Introduction

Starting from scratch

The starting point to conceive an experiment is understanding what particle physics experiments with accelerators look like, and finding an idea that stimulates your interest. What are you curious about? What would you like to measure? Keep in mind that you can get inspired by the proposals of the previous winners, by the document listing the example experiments, and by asking experts.

When you first meet with your team members, you are not expected to know much about particle physics, particle detectors, readout systems and data analysis, but a high level of curiosity and the will to learn new things will bring you a long way!

Once you have an idea, you should define which detectors and equipment you will need in order to measure the parameters that you are interested in. Read carefully this document, and do not hesitate to discuss with experts.

Once your idea is shaped, you should verify if it is feasible, if all the necessary equipment is available, and if it is precise enough. If you cannot figure it out by yourself, do not hesitate to get in touch with an expert or the BL4S team. You should also think about effects that can compromise the measurement and look for solutions to such problems.

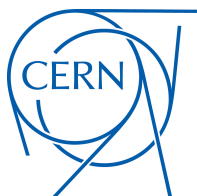
Finally, tell us in your proposal what you would like to measure, how you will do it, which problems you might encounter and what to you suggest to overcome them.

Particle accelerator experiments

Particle accelerators are machines able to propel charged particles at very high speed. Particles typically accelerated are electrons, protons or ions. There are two types of setups for experiments taking place at particle accelerators: fixed target experiments, and collider experiments.

In a fixed-target experiment the physics focus is on the interaction between a beam of accelerated particles and a target at rest. The interaction can happen both if the beam crosses a target or if it passes close to it. The target can be a solid, a liquid or a gas. Such experiments can have multiple purposes: investigating the particle beam itself, its interaction with matter, or even testing new detectors. Typically, the particle beam accelerated by an accelerator can be extracted and made available for experiments in several locations, known as beamlines. Each beamline can host one or more experiments. Each beamline has specific properties that need to be taken into account when an experiment is conceived.

In a [Collider](#) experiment (like experiments at the [Large Hadron Collider \(LHC\)](#)), accelerated particle beams, protons at the LHC, travel at close to the speed of light before they are made to collide head-on.



The configuration available for Beamline for Schools is that of a **fixed target experiment**.

Frequently used equipment

In a typical experiment, different devices are used to detect, identify or measure the properties of the particles, for example their path, their energy or their [Momentum](#). Devices that are commonly used are:

- [Scintillation counters](#), or scintillation detectors or just scintillators, for recording the passage of a charged particle. Please note that, like any detector, scintillators are not perfect. They will also give you signals when they are not hit by a particle. We call this noise. One way of eliminating this noise is to combine the signals of two scintillators in a coincidence module. These devices answer the question "did a particle pass through?".
- [Cherenkov Detectors](#), they record the passage of charged particles and they are able to provide information on some properties of the particles, and help with the particle identification. These devices answer the questions "did a particle pass through, and what kind of particle was it?".
- [Tracking](#) detectors for measuring the position of an electrically charged particle within the active volume of a detector. They answer the question "where did a particle pass through?"
- Electromagnetic [calorimeters](#), detectors that measure the energy of electrons, positrons and photons. They answer the question "what is the particle's energy?".

These detectors are *electronic* detectors: when a particle goes through them, an analogue electrical signal (for example a voltage or a current) is produced in different ways. For example, in a [Cherenkov detector](#) or a [scintillator](#), light is emitted when a particle goes through, and it is converted into an electrical pulse using a [Photomultiplier](#). In a gaseous [Tracking](#) chamber, a particle induces the generation of an electric charge.

The signals produced by the passage of a particle have a certain time duration, typically ~ 100 ns, and induce electric voltages ranging between 100 mV and 1 V. These signals are sent to a readout system where they are converted into a digital value, and eventually read out by a computer and stored to a hard disk. In silicon tracking detectors, the electrical pulse is converted to a digital value within the detector itself and the digital signal is read out by a computer.

Figure 1 shows an example of the experimental setup of a fixed target experiment at a beamline. This specific case is the setup of the "[Teomitzli Team](#)", one of the winners of the 2021 edition of BL4S at DESY. The goal of their experiment was testing a Cherenkov detector that they conceived. To do so, the incoming beam, from the right of the picture, first encounters a scintillation counter that detects the passage of the particles. Then, it goes through two trackers, it crosses the detector under analysis, it crosses another pair of trackers, that, together with the first two indicate the position of the particles and allow a good alignment of the detector under investigation, and it finally hits a last scintillator, that is used to generate the [Trigger](#) signal for the data acquisition.

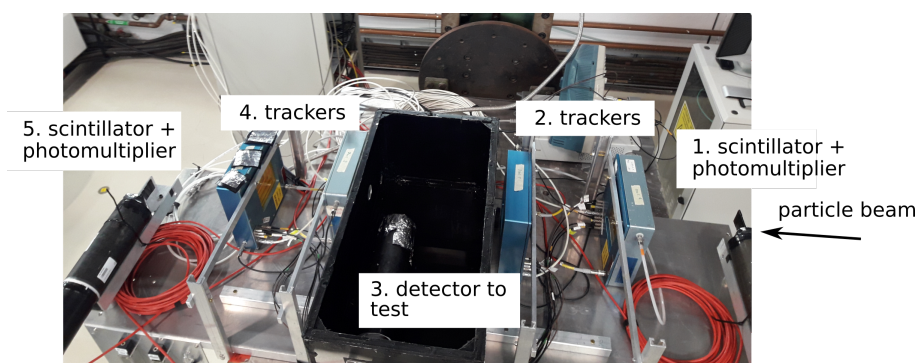
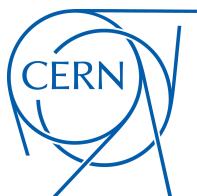


Figure 1: The experimental setup of one of the winning teams of the 2021 edition of the competition, the "[Teomitzli team](#)". The particle beam comes from the right, it first crosses a scintillator (1.), then 2 trackers (2.), it goes through the detector under test (3.), it crosses a second pair of trackers (4.) and it finally reaches a second scintillator (5.).

Examples of detectors in the BL4S experiments are described in more detail in the following chapters. **Keep in mind that you do not need to use all the detectors to build your experiment, and that you can bring your own detector to CERN.**

Trigger and readout

Particle physics experiments produce a large amount of data, and a system is required to decide which data are relevant for the physics you are interested in. This system is known as a [Trigger](#) and its role is identifying interesting interactions, usually called "events", and instructing 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



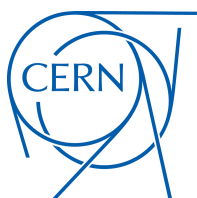
of interest¹.

In BL4S, the trigger is much simpler and it is built using signals from some of the detectors. A triggering system might, for example, require coincident signals from two or more scintillators along the beam path to indicate the passage of a particle (as in the setup shown in Figure 1). 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, information (light) is transferred to the charge coupled device (CCD), converted to digital data, and recorded to memory. One difference is that in the case of BL4S, the exposure time is about 100 ns.

Data Analysis

All the data collected by the different components of an experiment need to be carefully analyzed in order to understand their meaning, and to unveil the physics information. A large amount of software has been developed at CERN and elsewhere for the analysis of experimental data. The analysis software typically used for the purposes of BL4S is based on a framework called [Root](#), which is used by many physics laboratories all over the world. Keep in mind that you don't need to get familiar with the data analysis tools in order to prepare your proposal.

¹For example, the production of a Higgs [Boson](#) occurs in one out of a trillion events (where one trillion is 10^{12}).



The Beam Lines

The BL4S experiments take place in the T9 beam line at the [CERN Proton Synchrotron \(PS\)](#). The experimental area where the T9 beam line is located is one of the most intensively used facilities and it has been available to users for 56 years. The PS is a circular accelerator with a circumference of 628 m, it is part of the [CERN accelerator complex](#), and it accelerates protons up to an energy of 26 GeV.

You should know that in high-energy physics, the units for energy, [Momentum](#) and mass are [eV](#), [eV/c](#) and [eV/c²](#), respectively, where c is the speed of light. In the world of particles, these units are more practical than the [MKS units](#). The eV is defined as the energy acquired by an electron accelerated by a potential difference of 1 V: $1 \text{ GeV} = 1 \times 10^9 \text{ eV} = 1.6 \times 10^{-10} \text{ Joule}$, $1 \text{ GeV}/c^2 = 1.783 \times 10^{-27} \text{ kg}$. Time is usually measured in nanoseconds (ns), where $1 \text{ ns} = 10^{-9} \text{ s}$, which is the time it takes for light to move a distance of 30 cm. For comparison, the maximum energy of the [Proton](#) beam at the LHC is 6500 GeV.

You should also keep in mind that physicists often talk about [Momentum](#) instead of energy. Do not panic, the speed of light allows you to convert one quantity into the other.

The proton beam accelerated by the PS can be extracted and smashed into an aluminium or beryllium target. By carefully placing a series of devices, including magnets and absorbers, the debris resulting from this collision can be separated into beams of different particles that can be used for experiments in a beamline. These beams are known as "secondary beams".

In the following section the main devices used to guide the particle beams into the beam lines and optimize their properties are described.

Bending magnets

Bending magnets² are used in the beamline to guide the particles in a certain direction, and to choose the particle's momenta by setting the intensity of the magnetic field. A bending magnet is typically an electromagnet and the intensity of the magnetic field is modulated by the current flowing in it. These magnets are dipoles (Figure 2) with a vertically-orientated magnetic field. The particles that cross the field will be deflected horizontally, according to the Lorentz force.

²You might consider watching this short instructional [video](#), which shows how charged particles move when influenced by a magnetic field.

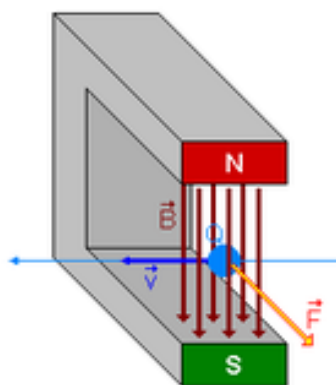


Figure 2: A dipole magnet with the vertical magnetic field and a charged particle moving horizontally into the field. The force is perpendicular to the magnetic field vector and the velocity vector, deflecting the charged particle horizontally. Image source: [Wikipedia](https://en.wikipedia.org/wiki/File:Diagram_of_a_dipole_magnet.png).

Collimator

A collimator is a tool used to filter a particle beam. There are two sets of collimators in the beam lines at CERN. The primary collimator defines the [Momentum acceptance](#) and [Beam divergence](#). A secondary collimator, placed in the test beam area, allows to further reduce the [Beam halo](#). The flux available, i.e. the amount of particles that crosses a defined area in a specific time interval, depends on the collimator settings. To clarify, the more a beam is filtered out by a collimator, the lower the flux is. Don't worry too much about the details of these collimators. The BL4S support scientists will set them up for you.

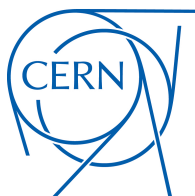
Beam Properties

The secondary beams available at the PS include different types of particles having an energy ranging between 0.2³ and 15 GeV. Bending magnets, collimators and two [Cherenkov detector](#) placed at the entrance of the experimental area are used to separate and identify the particle species.

Figure 3 and 4 show the composition of positive and negative beams respectively ⁴. It

³Please note that below 0.5 GeV the beam properties might be sub-optimal. If you need to work at low energy we suggest you to contact us.

⁴Please note that these plots stop at 10 GeV but the beam can reach an energy of 15 GeV. The reason is that this testbeam facility has been upgraded in 2020/2021 and an updated version of the plot is not available yet. Nevertheless, the data shown by the plots are still valid.



is not possible to have a beam of neutral particles (e.g. photons). The negative (positive) beam contains negatively (positively) charged particles: electrons (or [Positron, \$e^+\$](#)), [Anti-protons](#) (protons), [Pions](#), [Kaons](#) and [Muons](#). To know more about these particles we suggest you to watch this [video](#) or take a look at Wikipedia.

It is important to keep in mind that Kaons and Pions transform into [Muons](#) within a characteristic time of ~ 26 nanoseconds (for Pions), hence along their path to the testbeam area. Therefore, the beam contains a certain number Muons. Muons tend to interact with matter much less than other particles, hence, by closing the collimator (i.e. by putting an obstacle in the path of the beam) one can stop all the particles except for Muons. In this way, a beam consisting of Muons can be obtained. Other particles may be created by the collision of the beam with the air in the experimental area. These "undesired" particles create a background that might affect the results of an experiment and need to be considered. Please contact us if you need additional information.

The beam is not continuous in time but it follows the acceleration cycle of the PS. Hence, the particles arrive in bursts or spills, the [Flux](#) of particles depends on their Momentum and on their type. For example, Figure 4 shows that a beam of negative particles having a Momentum of 4 GeV contains ~ 450 antiprotons, ~ 10000 Electrons and Kaons and ~ 150000 pions per burst of 400 ms. The relative intensity of particles can be modified by changing the target used to convert the primary beam of protons into the secondary beam. One type of target provides a beam richer in hadrons, the second one richer in electrons.

Furthermore, there is also the possibility to have a very pure electron beam from the neutral channel. To do so, the secondary beams of charged particles are deflected away with two bending magnets and only the neutral gamma rays⁵ are selected. Following this, a converter consisting of 5 mm of lead is placed in their path and convert them into electron/positron pairs. Finally, the beamline is tuned to select either the electrons or positrons of energies ranging between 0.5 GeV and 4 GeV. Using this method, at energies < 3 GeV the electron purity is $> 90\%$.

The beam has more or less a round profile, known as cross section. In the focal plane, the beam spot has a diameter of about 2 cm. Similar to what happens with light, the further away the beam is from the focal place, the larger the diameter. The position of the focal point can be adjusted.

Take-home messages about the beam:

- The beam can be composed of positive or negative particles. The particles available are Protons, Electrons, Positrons, Antiprotons, Kaons, Pions, and Muons.

⁵Gamma rays are photons with energies above 0.5 GeV.

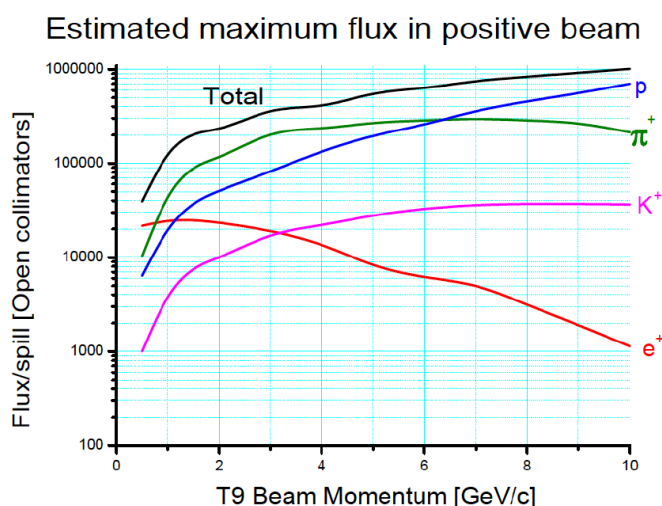


Figure 3: The **Flux** of positive particles present in the beam as a function of their **Momentum**. Please note that the flux is calculated over a time of 400 ms, and the most important information that you should retain from this plot is relative intensity of particles of different species.

- The particle energy ranges between 0.2 GeV and 15 GeV. At this energy, the particles are relativistic. As an example, the rest mass of a Pion is $0.140 \text{ GeV}/c^2$ and, with a momentum of $3 \text{ GeV}/c$, it will travel at the 99.891% of the speed of light.
- The particle flux depends on the type of particle and its energy. Protons and Pions are the most abundant particles in the beam. In the T9 one can (to a certain extent) select the type of particle.
- The beam spot size at the focal point is round with a diameter of 2 cm.

The T9 test beam areas

The BL4S experiments take place in an area that has a size of about $5 \text{ m} \times 10 \text{ m}$, where the equipment can be laid out according to your needs. Additionally, it may be possible to install devices that are brought by your team to the experimental area⁶. Each request will be reviewed individually and will need to respect health and safety guidelines. For example, the installation of large amounts of combustible material

⁶Please note that CERN cannot guarantee the installation of all the suggested devices.

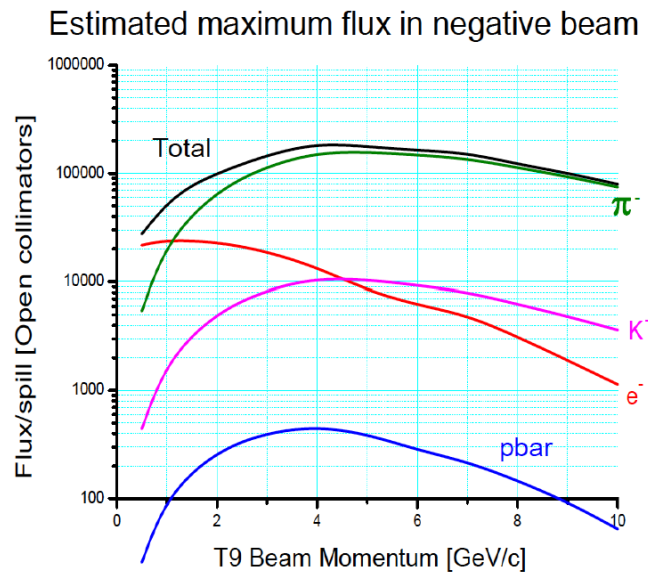
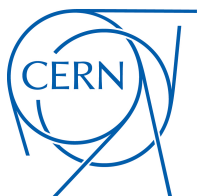


Figure 4: The **Flux** of negative particles present in the beam as a function of their **Momentum**. Please note that the flux is calculated over a time of 400 ms, and the most important information that you should retain from this plot is relative intensity of particles of different species.

(e.g. wood) is not possible for safety reasons. It is also not possible to expose any **Biological material** to the beam.



The BL4S detectors

Scintillation counter

A **scintillator** is a material that produces scintillation light, a property of luminescence, when excited by ionizing radiation⁷. Luminescent materials, when struck by an electrically charged particle, absorb some of the particle's energy and scintillate, i.e. re-emit, the absorbed energy in the form of light. A scintillation counter is obtained when a scintillator slab is connected to an electronic light sensor, a device that converts light into an electronic signal, 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 effect⁸. The subsequent multiplication of these photoelectrons results in an amplified, electrical pulse that can be analyzed; yielding meaningful information about the particle that originally struck the scintillator.

Several scintillators are available for installation in the experiment. The scintillators can be used for counting particles or for setting up the trigger logic. Fast scintillators can be used for timing the particles (i.e. measuring the time it takes for a particle to travel from one scintillator to another).

Halo counter

The halo counter is formed by a specific arrangement of scintillators placed around the beam, for example, a set of 4 **scintillators** that form a hole around the beam passage (Figure 5) or a single scintillator with a hole. 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 spread away from the beam axis, the halo counter identifies them and thus makes it possible to choose to either reject or flag them (i.e. identify them as interesting for a certain purpose). This is useful, e.g. for flagging particles that interacted with a certain absorber and underwent **Scattering**.

Delay Wire Chamber (DWC) / Tracker

The Delay Wire Chamber (DWC) is a 2D (two-dimensional) particle tracker consisting of a multi-wire chamber that can give the coordinates of the position of a particle that passed through. It uses an array of wires that are kept at high voltage and connected to a so-called delay line, i.e. an electric component able to determine how much time does a signal take to travel through it. The chamber is filled with gas (a mixture of argon and CO₂). Any **ionizing particle** that passes through the chamber will ionize

⁷You can watch a simple animation [here](#).

⁸The extraction of an electron from a material hit by photons

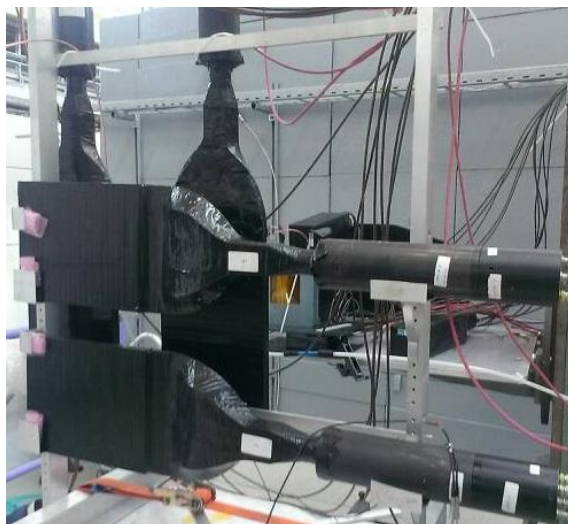


Figure 5: A Halo counter.

the atoms of the gas. The resulting ions and electrons are accelerated by an electric field across the chamber, causing a localized cascade of ionization. The signal from the wires builds up two electric signals in the delay line, one in each direction. By using a reference signal as a common start, and measuring the time delays for the signal to reach each end of the delay line, the impact point (i.e. where the first ionizing took place) can be determined.

The active area is $10\text{ cm} \times 10\text{ cm}$ and position resolutions (the smallest spatial separation that can be measured) of $200\text{ }\mu\text{m}$ – $300\text{ }\mu\text{m}$ can be achieved. The unit “ μm ” represents a micrometer, one millionth of a meter. However, the chamber can measure only one particle inside a certain time window of approximately 700 ns, this means that they can track up to $1 \cdot 10^6$ particles per second. Four DWCs are available for the experiment, if required.

Do not be scared by learning the functioning details of a DWC, the most important information to retain is what it can measure and what is its resolution.

MicroMegas detectors / Trackers

MicroMegas detectors serve the same purpose as DWCs; they allow you to track particles. Compared to the DWCs, they have a larger surface and a higher resolution. The disadvantage is that they are not as fast. With the electronics that will be used to read those out, we can at most track 500 particles per second. The MicroMegas detectors have a spatial resolution of about $200\text{ }\mu\text{m}$ and an active area of $40\text{ cm} \times 40\text{ cm}$. They are 1D (one dimensional) detectors and therefore able to record the position of

a charged particle in the vertical or the horizontal plane only. As there are four of them, you can build, by combining two of them, two 2D detectors. The MicroMegas, for example, can be used behind a fixed target to record the angle by which charged particles are scattered.

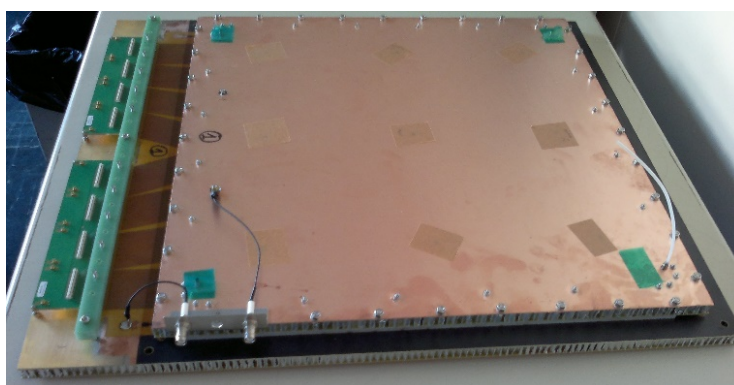


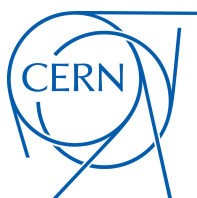
Figure 6: MicroMegas detector.

Silicon Pixel Detectors / Trackers

As the gaseous detectors described above, silicon pixel detectors are used for particle tracking by delivering a 2D information on where a particle has passed through. These detectors work very similarly to nowadays camera chips in mobile phones. When a highly energetic particle traverses the chip, it deposits a small amount of energy which is registered as a signal in the pixel cell it traversed. Since a Silicon Pixel Detector is not currently part of our selection of detectors, we encourage the teams who would like to use one to contact us. Keep in mind that Silicon Detectors are usually quite small, typically $2\text{ cm} \times 2\text{ cm}$, and they are sensitive to Gamma and X-Rays.

Time of flight measurements

In some cases it may be important to know the velocity of a particle. This can be done by measuring the time of flight over a known distance. Two scintillators or other detectors record the time at which the particle is seen at defined locations. By recording the time difference and the distance between the detectors, the velocity can be calculated. Note that the distance between the detectors can only be measured to an accuracy of 1 cm and the time to 200 ps ($200 \times 10^{-12}\text{ s}$).



Multi Gap Resistive Plate Chamber (MRPC) / Tracker

A Multi Gap Resistive Plate Chamber is a detector which is particularly suitable for [time-of-flight measurements](#) measurements because it can provide very accurate time information for the passage of a particle. In a well-calibrated system, values as low as 100 ps (10^{-12} s) can be reached. We have three MRPC with a surface area of 30 cm \times 30 cm.

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 plate while all interior plates are left electrically floating. 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*. You can use the MRPCs to check at which speed different particles are traveling.

Cherenkov Detectors

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 Cherenkov radiation (also known as Cherenkov light ⁹). 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 direction of the charged particle 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. For example electrons will always emit light in any gas, unlike the other particles. At a given momentum range the discrimination between Electrons, Muons and Pions is possible by tuning the pressure of the gas inside the detector.

Two Cherenkov detectors are part of the fixed setup. You can choose between different gases and tune the pressure of the gas according to what particles you would like to detect. If you choose not to use the Cherenkov detectors in your experiment, they will remain on the beam but can be evacuated, so that they will not interfere with the properties of the beam.

⁹You might want to see two instructional videos explaining Cherenkov light: [Particle Physics and Cherenkov light](#) and [Cherenkov light: What is it?](#)

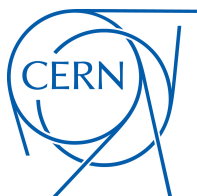
Lead crystal calorimeter

A lead crystal **Calorimeter** is a detector that measures the energy of impinging particles (therefore it is not a **Tracking** detector). An electron hitting the calorimeter will produce a fully contained **Electromagnetic shower**, depositing all its energy in the calorimeter and thus allowing a measurement of its energy. By measuring the deposited energy, the energy of the incoming particle can be measured. Beamline for Schools has 16 calorimeters, each having a volume of $10\text{ cm} \times 10\text{ cm} \times 37\text{ cm}$ (Figure 7). The energy resolution, σ_E , of the calorimeter is estimated, at energy E , as:

$$\frac{\sigma_E}{E} = 0.02\% + \frac{6.3\%}{\sqrt{E}}$$



Figure 7: Stack of lead crystal calorimeters.



Other infrastructure

A huge collection of so-called NIM modules (electronics modules used for specific purposes, for example selecting signals exceeding a certain threshold) are available for simple signal processing and trigger generation. Additional electronic modules for the read-out of the detectors as well as associated software will be provided by CERN. We do not expect you to design the read-out system of your experiment. This will be done by experts of CERN for the winning proposals.

Data Acquisition

BL4S 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. Please keep this limit in mind. Do not propose experiments that look for effects that are extremely rare.

The data acquisition system provides tools for the on-line monitoring of the experiment in the form of histograms.

Don't worry about the details of this system. Experts of CERN will help the winners of BL4S to set-up the system and will also provide code for and assistance with the analysis of the data.