Beams and detectors

Beamline for Schools 2026

Contents

Introduction

Beamline for Schools (BL4S) is a physics competition for high-school students from all around the world organised at CERN, the European Laboratory for Particle Physics, in Geneva, Switzerland, and DESY, the German Electron Synchrotron, in Hamburg, Germany. Teams of high school students can propose an experiment that they want to perform at a beamline, that is, a part of a particle accelerator.

In **2026** there will be five winning teams. Two teams will perform their experiments at CERN, and one team will be invited to DESY. The organisers of BL4S will decide which winning team goes where to make sure that each team will be assigned to the laboratory that best matches the requirements of their proposal.

In this document, you will learn more about the properties of the **beams at CERN and DESY** and the **detectors and instruments available for your experiments**.

Starting from scratch

When you first meet with your team members, you don't need to know much about particle physics, detectors, data acquisition or analysis. Your curiosity and your wish to learn new things will bring you a long way!

For designing your experiment, your first steps are to understand how particle physics experiments at accelerators typically work and to find an interesting research idea for you. *What are **you** curious about? What would **you** like to learn more about?*

It is not necessary to propose a very ambitious experiment to succeed in the BL4S competition. We are looking for experiment proposals that are creative and feasible and that follow a scientific method. Get inspired by the proposals of the previous winners and by the document listing the **BL4S example experiments**. This document provides you with short descriptions of different experiments that you could conduct with the beam and detectors available for BL4S. **We encourage you to use them in your proposals!**

Once you have an experiment idea, investigate - with the help of this document - whether it is feasible: *Could the experiments be conducted with the beam and detectors available for BL4S or with material that you can provide? Are the detectors precise enough? What problems could compromise the measurement, and what are possible solutions to overcome them?*

We encourage you to reach out for support to experts in your local university and to the **BL4S contact people** from all over the world who are happy to interact with you and to provide you with additional information and advice.

Finally, tell us in your proposal your research idea, what parameters you would like to measure, how you will do it, which problems you might encounter, and how you suggest overcoming potential problems. The evaluation of your experiment proposal will take into account the following criteria:

- Motivation to participate in BL4S
- Motivation of the experiment
- Scientific method
- Feasibility of the experiment
- Creativity of the experiment

Physics experiments at particle accelerators

Particle accelerators can accelerate electrically charged particles, such as electrons, protons or different ions. Acceleration means to change the speed or the direction of movement of the particles. When a particle's speed is increased, its energy is also increased. Usually, particle accelerators accelerate many particles at the same time. We call all these particles together the **beam**. That is, the term "beam" refers to a large number of particles moving in the same direction. There are two types of experiment setups possible at particle accelerators: **fixed-target experiments** or **collision experiments**.

In a **fixed-target experiment**, the physics focus is on the interaction between the beam (i.e. a large number of particles moving in the same direction) and a target at rest. The interaction can happen when the beam moves through a target or when it moves very close to it. The target can be a solid, liquid or gaseous material. Fixed-target experiments can have multiple purposes: investigating the beam itself, its interaction with matter or testing out a new detector. Fixed-target experiments happen at so-called **beamlines**. The term "beamline" refers to a straight section of a particle accelerator leading the particles to an experimental area. Each beamline can host one or more experiments, and has specific properties that need to be taken into account when designing an experiment.

In a **collision experiment**, the physics focus is on the interaction between two beams. These beams travel in opposite directions at nearly the speed of light before colliding with each other, for example, at the Large Hadron Collider (LHC).

In Beamline for Schools, you can only conduct fixed target experiments with different types of electrically charged particles (see Beamlines). *Please consider this when designing your experiment.*

The **beam used for the BL4S experiments at CERN** doesn't contain neutral particles.[1] Yet, the interaction of the beam with a target may produce neutral particles

[1] Although neutral particles are created at the target, they cannot reach the experimental area as neutral particles are not affected by the bending magnets that steer the beam to the experimental area.

(e.g. neutrons, neutrinos). Most of our detectors are not able to detect neutral particles; one notable exception is the WENDI detector for neutrons.

Commonly used units

Particle physicists often use units other than the SI units Joule and Kilogram to express energies or masses. In particle physics, **energies** are given in the unit electronvolt, short eV, which is the product of the elementary charge e and the unit of voltage V. The eV is defined as the energy gained by one electron accelerated by a potential difference of 1 V. For example, the maximum energy of the protons accelerated in the LHC is 6800 GeV, where 1 GeV = 1×10^9 eV = 1.6×10^{-10} Joule.

Moreover, particle **masses** are given in the unit eV/c^2, where c is the speed of light (i.e. the speed of photons). For example, the mass of electrons is 511 keV/c^2, the mass of protons is 938 MeV/c^2, and the Higgs boson mass is 125 GeV/c^2, where 1 GeV/c^2 = 1.783×10^{-27} kg. This unusual unit makes it much easier to know how much collision energy is needed to create a certain type of particle. For example, a collision energy of at least 125 giga-electronvolts (GeV) is needed to create one Higgs boson.

The unit for **momentum** is eV/c. Note that physicists often talk about momentum instead of energy. Luckily, you can rather easily convert momentum to energy and vice versa using the speed of light (c).

Time is usually measured in nanoseconds (ns), where 1 ns = 10^{-9} s, which is the time it takes for photons to move a distance of 30 cm.

Commonly used equipment

Several devices are used to detect and identify particles, and to measure their properties (e.g. trajectory or energy). Commonly used devices are:

- **Scintillation detectors** are used to detect electrically charged particles. Whenever such a particle passes through the scintillation detector, you get an electric signal. Scintillation detectors answer the question **"did a particle pass through?"**.

- **Cherenkov detectors** also detect electrically charged particles. In addition, they can provide information on some properties (e.g. speed) of the particles. Hence, Cherenkov detectors answer the questions **"did a particle pass through and what kind of particle was it?"**.

- **Trackers** are 2D or 3D (two- or three-dimensional) detectors. Hence, they measure the position of an electrically charged particle within the sensitive area of the detector. They answer the question **"where did a particle pass through?"**.

- **Magnets modify the trajectory of electrically charged particles** according to their electric charge and their velocity (Lorentz force). Therefore, they can separate particles with opposite electrical charges or, if combined with tracking detectors, give information about a particle's momentum. Hence, magnets are usually used together with trackers.

- **Electromagnetic** calorimeters measure the energy of electrons, positrons, and photons. They answer the question **"what is the energy of the particle?"**.

Please note that no detector is perfect. The detectors will even give you signals when no particle passes through. We call this "noise". One way of eliminating noise is to combine the signals of two detectors in a coincidence module. **You do not need to use all the above-listed detectors to conduct your experiment.** You can also bring your own detector, if required for your experiment.

Exemplary experimental setup

Figure 1 shows an example of the experimental setup of a fixed-target experiment at a beamline, particularly the setup of the "Teomitzli Team", one of the winners of the 2021 edition of BL4S at DESY. The goal of their experiment was to test a Cherenkov

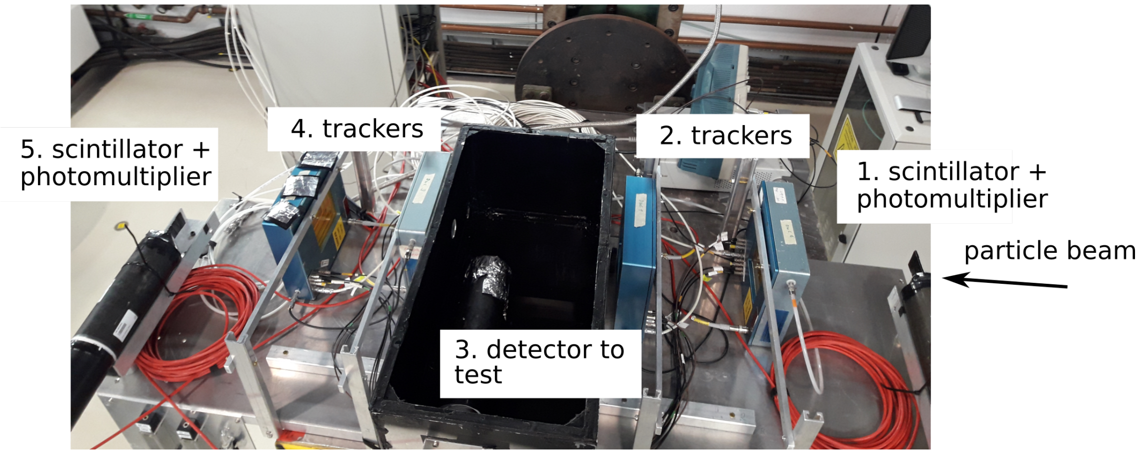


Figure 1: The experimental setup of one of the winning teams of the 2021 edition of BL4S, the "Teomitzli team". The beam comes from the right-hand side. First, it crosses a scintillator (1.); then, 2 trackers (2.); and the newly designed detector (3.). Finally, it crosses another pair of trackers (4.) and another scintillator (5.).

detector that they had designed. First, the incoming beam (coming from the right hand side of the picture) passes through a scintillation detector that can indicate that a particle passed through (1.); then, through two trackers that can indicate where a particle passed through (2.); followed by the newly designed detector that the team wanted to test (3.); another pair of trackers that can indicate where a particle passed through (4.); and through another scintillation detector that can indicate that a particle passed through (5.). Both scintillation detectors combined in a coincidence module are used to generate the trigger signal for the data acquisition, making sure that only particles that passed through the full setup are considered.

Data acquisition

When an electrically charged particle passes through a detector (e.g. scintillator), an analogue electrical signal (e.g. a voltage) is generated (see Basic principles of particle detection) and transformed into a digital signal by means of some special electronic modules. These signals are the data that we want to analyse. Particle physics experiments produce a huge amount of data. Hence, a data acquisition system is required to decide **which data should be read out**. Ideally, only the data relevant to the physics phenomenon you are interested in (i.e. the data you need to answer your research questions) is read out. Hence, a very important part of the data acquisition system is the **trigger**. Its role is to identify interesting interactions - usually called “events” - and, if there is an interesting event, to instruct the computer to read out the data from all the detectors.[2]

The **trigger** is usually built by combining the signals from some of the detectors. The trigger might, for example, require signals from two or more scintillators along the beam path in coincidence to indicate that a particle passed through the full setup. For example, in the setup shown in Figure 1, the two scintillators - (1.) at the beginning of the beam path through the setup and (5.) at the end - are used as a trigger. When a trigger occurs, data from all detectors is read out and sent to a mass storage, usually a hard disk. This mechanism is very similar to when you take a picture with a digital camera. When the shutter-release button is pressed (=trigger), photons hit the sensitive area of the camera (=detector), the photons are ultimately transformed into a digital signal (=data), and this data is stored on the mass storage. One difference is that in the case of BL4S, the exposure time is only about 100 ns.

We do not expect you to design the data acquisition system to trigger and read out the detectors of your experiment. BL4S will provide a data acquisition system for the winning experiments.[3] For example, at CERN, this system is fast enough to trace

[2] The trigger is a fundamental and very complex component of LHC experiments, where interaction rates are very high and only a very small fraction of the interactions are of interest. For example, a Higgs boson is only produced in one out of a trillion interactions (where one trillion is 10^{12}).

[3] The data acquisition system also provides tools for the online monitoring of the experiments in the form of histograms.

typically 3000 particles per second. Please keep this limit in mind and do not propose experiments that study extremely rare effects!

Data Analysis

For answering your research question, you will need to **analyse the data** collected with the different detectors in your experiment. Dedicated software has been developed at CERN, DESY, and elsewhere to analyse experimental data. The analysis software typically used in BL4S is based on a framework called ROOT, see Figure 2. ROOT is used by many physics laboratories all over the world. However, you don't need to get familiar with the data analysis tools when preparing your proposal. BL4S will provide the winning teams with the software needed to analyse the collected data, as well as some code and assistance with the data analysis.

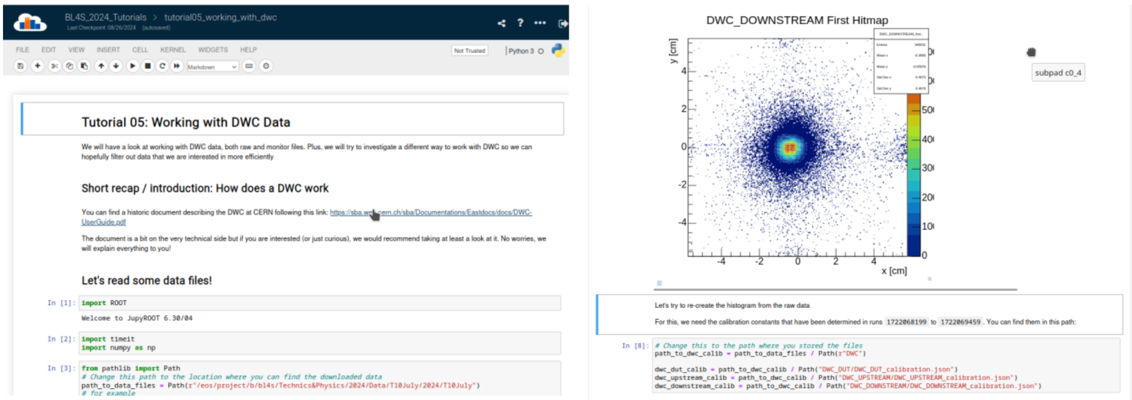


Figure 2: Screenshot of a typical Jupyter notebook using the Python interface to perform data analysis with ROOT.

Beamlines

In particle physics, the term **"beam"** refers to a large number of particles moving in the same direction. These particles can be accelerated to high energies. **Beamlines** are straight sections of a particle accelerator leading the particles to an experimental area. In such experimental areas, **fixed-target experiments** are conducted. Below, we first describe the beam properties at DESY and CERN. Then, we describe two important devices used to shape the beam, namely bending magnets and collimators.

Beam properties at DESY

The beam used in BL4S at DESY is a pure electron beam or a pure positron beam with energies ranging from 1 to 6 GeV. You can choose the properties of the beam needed for your experiments:

- **Particle type**: electrons or positrons.
- **Particle momentum**: any value between 1 GeV/c and 6 GeV/c.
- **Momentum spread**: typically, the momentum spread is around 0.15 GeV/c.

Beam composition and intensity

The number of particles making up the beam depends on the secondary target used when creating the beam (see Beam production (optional reading)), the selected momentum and the type of particle. For example, figure 3 shows the typical **rates** (i.e. the number of particles per unit of time) of electrons available in the experimental area at DESY, depending on the different particle momenta for different secondary targets. Please note that the particles are moving at almost the speed of light and are, hence, relativistic. The beamline at DESY usually provides **one particle at a time**. The particles arrive continuously within an 80-ms cycle, depending on the chosen energy. At high energy, one receives particles, for example, for 20ms and then not for 60ms, and so on; while at low energy one receives particles, for example, for 50ms and then not for 30ms, and so on. In sum, the **rate is much lower at high energy** than at low energy. Please note that experiments that require a large number of particles (i.e. for irradiation of materials, for collecting enough data for statistical purposes, to search for rarely occurring phenomena, etc.) are better suited for CERN since the overall number of particles can be much higher there.

The beam has a round cross-section. The diameter of the beam is **2 cm** when entering the experimental area. Similar to what happens with light, the further away the beam is from the entrance window, the more it spreads, that is, the diameter becomes wider.

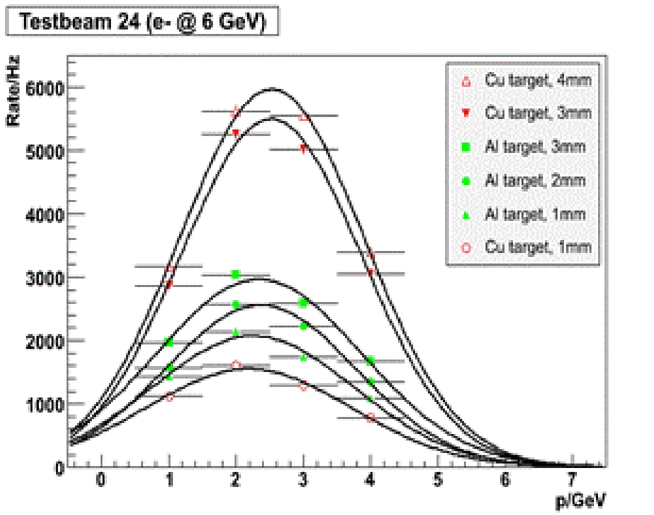


Figure 3: Typical **rate of the single electron beam in the experimental area at DESY** depending on the particle momentum. Rates are shown for different types and thicknesses of the secondary target.

The experimental area at DESY

The BL4S experiments at DESY take place in the **DESY II Test Beam Facility**. The experimental area has a size of about 5 m × 10 m. In this experimental area, the detectors and other equipment can be placed according to the needs of your experiment. In the experimental area, there are some fixed installations, such as a big red magnet (see The big red dipole magnet at DESY).

Beam production (optional reading)

The particle accelerator is called DESY II, and it is a Synchrotron accelerating electrons up to an energy of 6.3 GeV. Figure 4 shows how the beam is generated at the DESY II Test Beam Facility.

Inside the DESY II accelerator, Bremsstrahlung photons are produced by putting a target, called the primary target, into the electron beam. The primary target consists of a 7 µm thick carbon fibre. When the electrons move through the target, they lose some of their kinetic energy. This energy is transformed into photons, respecting the law of energy conservation. The photons move towards another target, called the secondary target. The secondary target is made of a few mm-thick metal plates. When the photons move through the target, their energy is transformed into pairs of electrons and positrons, again respecting the law of energy conservation. The electron/positron pairs then pass a dipole magnet followed by a collimator (see Bending magnets and

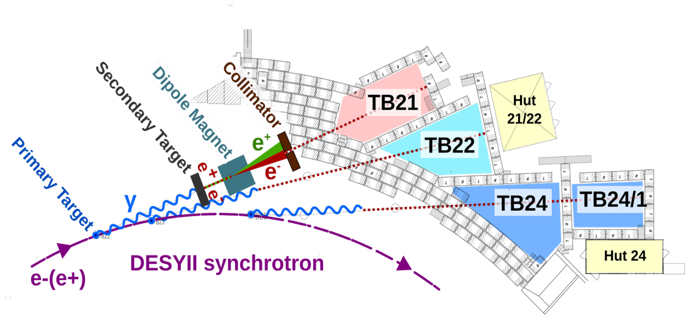


Figure 4: Sketch of the beam production at DESY II.

Collimators). By changing the field strength of a dipole magnet and the opening of the collimator placed after the magnet, one can choose the properties of the beam in the test beam area: One can either have a pure electron beam or a pure positron beam with momenta ranging from 1 to 6 GeV/c. It is **not** possible to have a beam of photons.

Beam properties at ELSA (The University of Bonn)

At the detector test beamline of ELSA, we can provide a monochromatic electron beam with a varying energy between 0.8 - 3.2 GeV. The extraction rate is user-controllable, continuously variable between 1 Hz and 625 MHz and the spill times vary from 3 s and 60 s with a 2 s pause between spills.

	energy E	$\frac{\Delta E}{E}$	width/mm	divergence/mrad	rate	current
Min	0.8 GeV	< 0.2 ‰	$\sigma_x = 1.3$ $\sigma_z = 1.0$	$\sigma'_x = 0.13$ $\sigma'_z = 0.01$	1 Hz	≈ 0 A
Max	3.2 GeV	< 0.8 ‰	$\sigma_x = 9.0$ $\sigma_z = 6.0$	$\sigma'_x = 2.5$ $\sigma'_z = 3.0$	625 MHz	100 pA

each independently adjustable

Figure 5: Beam properties and possiblecombinations at ELSA

Beam conditions

We support two types of beamtime, one as a secondary user, one as an exclusive primary user:

1. Simultaneous operation in combination with hadron physics experiments (highly preferred mode!, cost-efficient!)
    - Secondary user
    - Energy fixed to either 2.9 GeV or 3.2 GeV (depending on running primary experiment)
    - Extraction rate is user-controllable, but limited to 1 Hz up to 100 kHz
    - Spill time fixed to 4 to 8 seconds (depending on running primary experiment)
2. Exclusive operation for the detector test beamline (not preferred)
    - Primary, exclusive user
    - Energy user controllable between 0.8 GeV and 3.2 GeV (change in energy takes roughly 1 to 3h for beam setup)
    - Extraction rate user controllable, 1 Hz up to 625 MHz
    - Spill time variable from 3 up to 60 seconds

Notes:

- FLASH mode: Additionally, we can provide 250 ns, up to 2 nC electron pulses for high dose rate studies, corresponding to 40 MGy/s or up to 8 mA. These pulses can be delivered only at an energy of 1.2 GeV and only every 10 to 20 seconds (depending on charge)

Beam diagnostics at Accelerator:

- Chromox screens for beam position and size measurement for high rates (100pA) or in FLASH mode
- Scintillator for rate measurement and control (-> feedback to accelerator), signal also available for users

Detectors

- We can supply scintillators with varying sizes from 1.5cm x 1.5cm to 20cm x 20cm.
- We can provide a beam telescope with 6x Mimosa26 sensors (ANEMONE telescope) specs: 18.4 um pitch (tracking resolution of a few um), 115 us rolling shutter readout, binary charge info, 2x1 cm^2 active area

- We can provide a "time reference plane" (ATLAS FE-I4) (50x250 um pixels, 25ns timestamping, 2x2cm² active area)
- We can provide an AIDA TLU as a trigger system or an EUDET TLU (old version of TLU)
- We can provide a GridPix-based Time Projection Chamber (TPC) with 3 cm drift length and a 1.5 cm × 1.5 cm readout area. Spatial resolution of 50µm. The energy sensitivity depends on the chosen gas mixture, and sensitive to electrons, soft X-rays, and charged particles can be detected.
- To be used with the TPC, we can provide a gas mixing unit for precise ratio control and a vacuum pump for lower pressures. Common gasses such as Ar and He mixtures with CO2 are readily available while the other gases can be procured upon request for specific applications.

Magnets

We are not able to provide a magnet.

TDAQ system

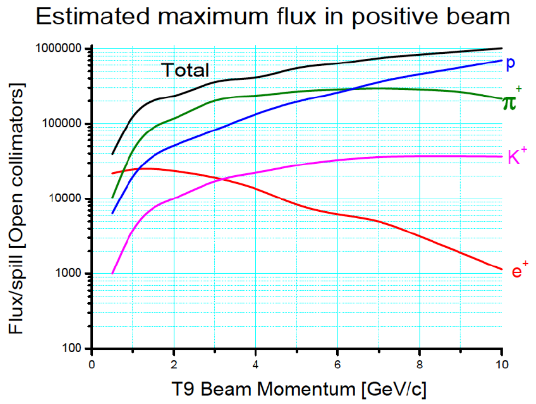
We can provide a NIM crate with many modules for setting a trigger logic.
We use "pymosa" for DAQ of the beam telescope (https://github.com/SiLab-Bonn/pymosa).
We use pybar for DAQ of time reference (https://github.com/SiLab-Bonn/pyBAR).
We use the Scalable Readout System of RD51 for the DAQ of the TPC (adaptors and FECs). However, taking data using both the beam telescope and TPC is challenging,g so experiments requiring the use of both are not desired.

Beam properties at CERN

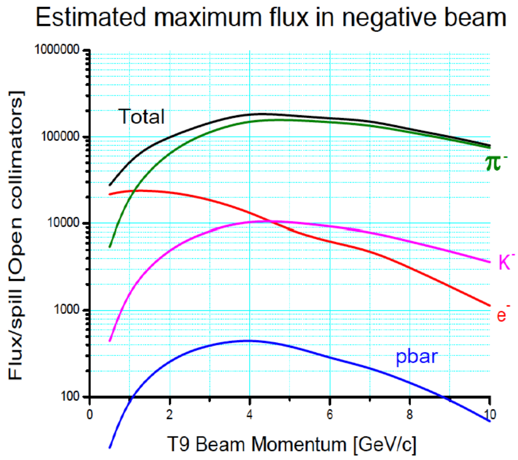
The beam used in BL4S at CERN is made of different types of particles, and it is, hence, a **mix of different types of particles**. The beam's **momentum ranges from 0.5 to 15 GeV/c**.

Beam composition and intensity

The beam is characterised by the **flux**, that is, the number of particles per unit of time and area. Since the beam for BL4S at CERN is made of different types of particles, there is a flux for each particle type. Based on the flux per particle type, one can draw conclusions about the composition of the beam. Figures 6a and 6b show the



(a) The flux of positive particles present in the beam as a function of their momentum.



(b) The flux of negative particles present in the beam as a function of their momentum.

Figure 6: The Flux (i.e. the number of particles per unit of time and area) of (a) positive and (b) negative particles in the beam as a function of their momentum. The flux is calculated over a time of 400 ms, and the most important information that you should retain from this plot is **relative number of particles of different types for the different momenta**. Note that muons are not in these graphs as they are created via pion or kaon transformation.

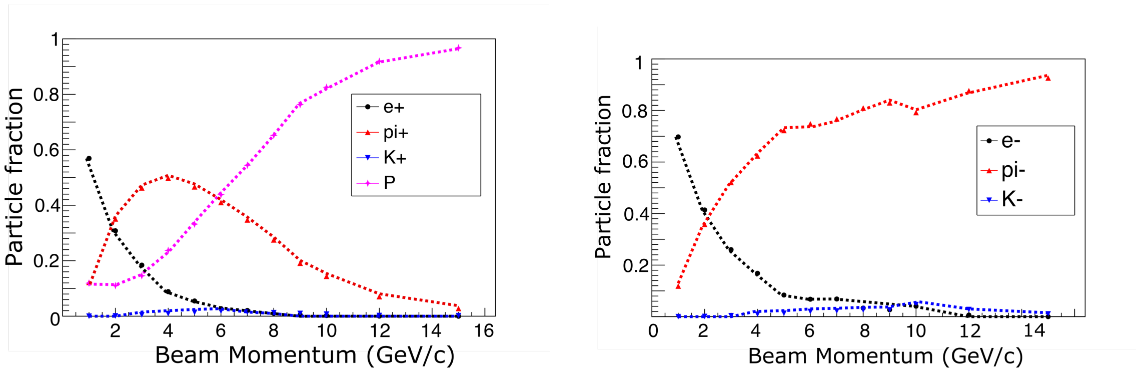
composition of positive and negative beams, respectively[4]. The negative beam is composed of negatively charged particles: electrons, antiproton, pions, kaons and muons. The positive beam is composed of positively charged particles: positrons (=anti-electrons), protons, pions, kaons and muons.[5] The Flux of the different particle types depends on their momentum and on their type.

Figure 6b shows that a beam of negative particles with a momentum of 4 GeV contains ∼450 antiprotons, ∼10000 Electrons and Kaons and ∼150000 pions per 400 ms. Please note that it is not possible to have a beam of neutral particles (e.g. photons).[6] The **fraction of the different particle types making up the beam** (i.e. how many particles of one type there are relative to the other types) as a function of the beam momentum with the hadron rich target is shown in Figures 7a (for positive

[4]Please note that these plots stop at 10 GeV/c but the beam can reach a momentum of 15 GeV/c. The reason is that this testbeam facility was 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.

[5]To learn more about these particles, we suggest you watch this video or take a look at Wikipedia.

[6]The relative number of particles can be modified by changing the target used to create the beam. One type of target provides a beam richer in hadrons, the other type provides a beam richer in electrons. However, we usually cannot choose the target.



(a) Positively charged particles (b) Negatively charged particles

Figure 7: The fraction of the different particle types making up the beam (i.e. how many particles of one type there are relative to the other types) for (a) positively and (b) negatively charged particles as a function of their momentum with the hadron-rich target. Note that muons are not in these graphs as they are created via pion or kaon transformation.

particles) and 7b (for negative particles).

For example, a fraction of 0.3 means that 30% of particles making up the beam are of one type (e.g. at 2 GeV/c the positively charged beam is made up of 30% positrons and 30% pions, see Figure 7a). The Figures 7a and 7b have been produced after the recent renovation of the test beam facility at CERN and complement Figures 6a and 6b.

Keep in mind that Kaons and Pions transform into other particles along their path to the test beam area. For example, Pions transform into muons (with a characteristic half-life time of $\sim$ 26 nanoseconds). Therefore, the beam contains a certain number of muons.

Moreover, it is possible to have a **very pure electron beam** or a **very pure positron beam** at CERN with an energy ranging from 0.5 GeV to 4 GeV.[7] In addition to the mixed beams with relatively small muon fractions, it is also possible to obtain a **relatively pure muon beam** with an energy ranging from 0.5 GeV to 3 GeV.[8]

[7] To create a pure electron/positron beam the beam of charged particles is deflected away with two bending magnets and only the neutral photons (in the gamma range with energies above 0.5 GeV) are selected. Following this, a converter consisting of 5 mm of lead is placed in their path and converts them into electron/positron pairs. Finally, the magnets and collimators of the beamline are 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%.

[8] Muons tend to interact much less with matter 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. By tuning the beamline's magnets and collimators, one can select different momenta of the muon beam. However, a high purity (80- 90%) muon beam is only available with energies up to 3 GeV. Above that,

The beam at CERN is not continuous in time. The particles arrive as part of a larger group - we say they arrive in "**spills**" - which typically lasts approximately. 400 ms. Within such a spill, the particles still pass through our experimental area and your setup one by one. You can typically expect to receive 1-3 spills per minute (see Figure 8).

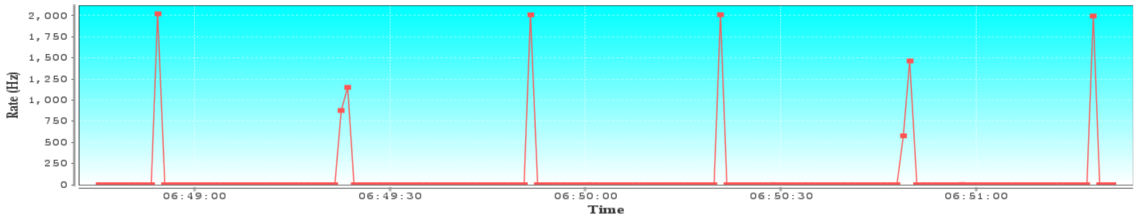


Figure 8: The flux rate at CERN. Particles are not delivered continuously to the experimental area but arrive in spills of approximately. 400 ms duration. Each "spike" in the plot corresponds to one of these spills.

The overall number of particles can be much higher at CERN than at DESY, easily reaching 10^4 to 10^5 particles in one spill for certain configurations. Therefore, experiments that require a large number of particles (i.e. for irradiation of materials, for collecting enough data for statistical purposes, to search for rarely occurring phenomena, etc.) are, in principle, better suited for CERN.

The beam has a round cross-section. When focused, the beam spot has a diameter of about 2 cm. Similar to what happens with light, the further the beam moves, the larger the diameter. The focus of the beam can be adjusted to some extent.

The experimental area at CERN

The BL4S experiments at CERN take place in the **PS Test Beam Facility**. The experimental area has a size of about 5 m $\times$ 10 m, and the equipment can be put according to your experiment's needs (see Figure 9).

Two Cherenkov detectors and two scintillation detectors are fixed installations at the entrance of the experimental area at CERN. In addition to the equipment provided by BL4S, it may be possible to install devices that are brought by your team to the experimental area[9]. Each request will be reviewed individually and will need to respect health and safety guidelines. For example, the installation of large amounts of combustibles (e.g. wood) or biological material is not possible for safety reasons.

other particles are also present in increasing numbers and have to be accounted for.

[9] Please note that CERN cannot guarantee the installation of all the suggested devices.

Figure 9: The experimental area at CERN with the experimental setup of the two winning teams of BL4S 2022.

Beam production (optional reading)

At CERN, the BL4S experiments take place in the Test Beam Facility of the CERN Proton Synchrotron (PS). This test beam facility is one of the most intensively used facilities and has been available to users for 63 years. The PS is a circular accelerator with a circumference of 628 m. It is part of the CERN accelerator complex, and accelerates protons up to an energy of 26 GeV.

The protons accelerated by the PS can be brought into collision with an aluminium or beryllium target. When the protons collide with the target, the collision energy transforms into new particles, respecting the law of energy conservation. These particles are called "secondary particles" and can be used for experiments in a beamline.

Take-home messages about the beam

- The beam at **DESY** is a pure electron or positron beam with momenta ranging from 1 GeV/c to 6 GeV/c.
- The beam at **CERN** is either positively charged or negatively charged and contains protons/anti-protons, positrons/electrons, kaons, pions, and muons. The particle momentum ranges between 0.5 GeV/c and 15 GeV/c.
- At these momenta, the particles are **relativistic**. 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 travel at the 99.891% of the speed of light.

- The particle flux of the CERN beam depends on the type of particle and its momentum. Protons and pions are usually the highest fraction of particles in the beam. One can - to a certain extent - select the type of particle.
- Both at CERN and DESY the cross section of the beam at the focal point is **round with a diameter of 2 cm**.

Bending magnets

Bending magnets[10] are used in beamlines to **change the direction of movement of electrically charged particles**. Moreover, the particles' momenta can be selected by changing the strength of the magnetic field. Hence, bending magnets are typically electromagnets. The strength of the magnetic field can be changed by changing the current intensity. These magnets are dipoles (Figure 10) and the magnetic field is oriented vertically. The particles passing through the magnet will be deflected horizontally, according to the Lorentz force.

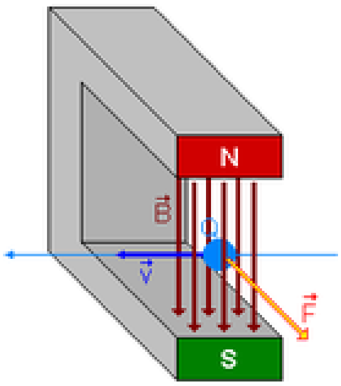


Figure 10: A dipole magnet with a vertical magnetic field and a charged particle moving horizontally through the field. The force is perpendicular to the direction of the magnetic field and the direction of movement of the charged particle, deflecting the charged particle horizontally. Image source: Wikipedia.

[10]You might consider watching this fantastic video, which provides a great introduction to the electromagnetic field and shows how charged particles move when influenced by a magnetic field (Lorentz force: from 14:51 to 20:58).

The big red dipole magnet at DESY

At DESY, a large dipole magnet is a fixed installation in the experimental area where the BL4S experiments usually take place. It is a dipole electromagnet and is called "big red magnet". It provides a magnetic field up to 1.35 T (see Figure 11). It has an integrated length (i.e. depth) of about 1 m and an opening that is about 1.5 m wide and 0.35 m high.

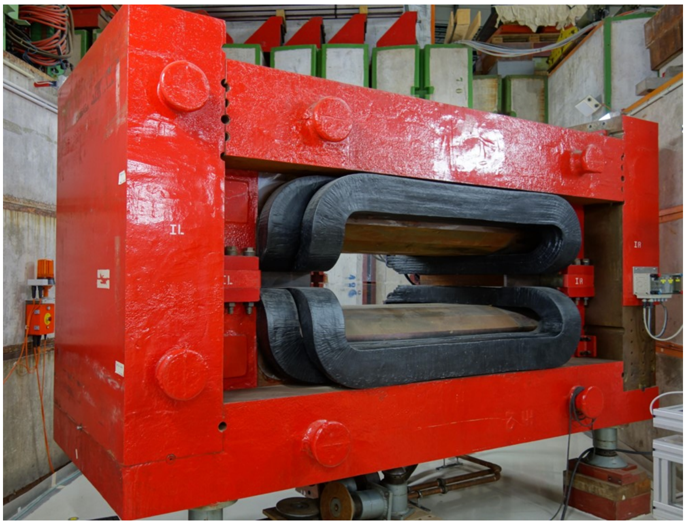


Figure 11: Big Red Magnet, 1.35 T dipole electromagnet

Magnets at CERN

It is possible to install a dipole electromagnet in the experimental area at CERN where BL4S usually takes place. Please contact us if you need a magnet for your experiment.

Collimators

Collimators are used to filter the beam. Typically, collimators are used to define the momentum acceptance, the beam divergence, or to reduce the beam halo. The flux available (i.e. the number of particles that cross a defined area in a specific time interval) depends on the collimator settings. The smaller the opening of the collimator, the lower the flux of the beam. Don't worry too much about the details of these collimators. The BL4S support scientists will set them up for you.

The BL4S detectors

Further information about the different detectors available for your experiments.

Basic principles of particle detection

For a particle to be detected, it needs to create an electrical signal. To do this, the particle must interact with the material of the detector by transferring energy to it. The electrical signal is usually induced by moving electrons. Therefore, the original particle (whether it is electrically neutral or charged) must go through a process of transformation, until electrons are freed that then move through the detector material (see Figure 12).

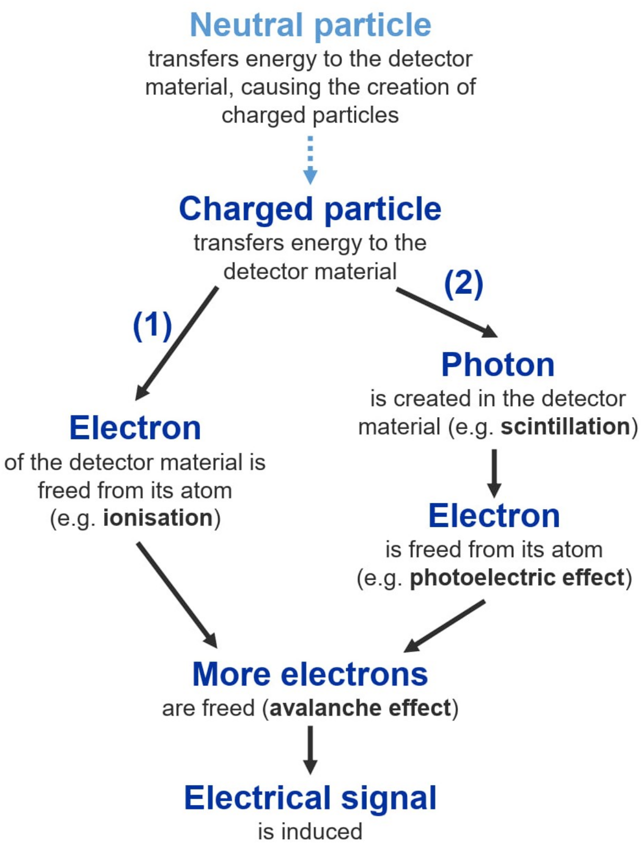


Figure 12: Illustration of the two main ways in which a particle can be detected. Image source: Physics Education Article

If the original particle is neutral, it must first cause the production of electrically charged particles. There are several processes by which this can happen, for example, pair-production or strong interactions with nuclei of the material. Once there is an electrically charged particle (either original or from a neutral particle), there are two main ways in which it can interact with the detector material: (1) by directly freeing electrons from the material or (2) by first creating photons that subsequently free electrons. In both instances, the electron needs to free even more electrons to induce a measurable electrical signal. Below, we will explain the two ways in more detail.

(1) The electrically charged particle directly frees electrons (e.g. ionisation): An electrically charged particle transfers some of its kinetic energy to the material of a gas detector or a semiconductor detector. In a gas detector, an electron of the gas gains the transferred energy and is, thus, freed from its atom, leaving an ion. This process is known as ionisation. The process is similar in semiconducting detector materials, where so-called electron–hole pairs are created, with the main difference being that an electron needs to gain less energy to be freed in a semiconductor than in a gas detector.

(2) The electrically charged particle creates photons (e.g. scintillation or Cherenkov) that subsequently free electrons (e.g. photoelectric effect): An electrically charged particle transfers some of its kinetic energy to a detector, creating a photon (e.g. scintillation or Cherenkov). At the end of the detector, the created photon hits a metallic surface and is absorbed by an electron, causing this electron to be freed. This is known as the photoelectric effect.

Whether the electron is freed (1) directly by the electrically charged particle, or (2) indirectly via a photon, **many more electrons must be freed to finally induce a measurable electrical signal**. By applying a very strong electric field, the initial electron gains sufficient kinetic energy to free more electrons, which can in turn be accelerated and free even more electrons. This process is called the **avalanche effect** and it results in an amplification of the number of free electrons. As the electrons travel towards the anode, **electrostatic induction** occurs. This is the **electrical signal** that we read out.

BL4S detectors of type (1)

Delay Wire Chambers (DWCs)

The Delay Wire Chamber (DWC) is a 2D (two-dimensional) gas-filled particle detector based on ionisation (see Basic principles of particle detection). DWCs can give the x- and y-coordinates of the position of a particle that passed through, that is, they can tell **where did a particle pass through the plane of the detector**. The sensitive area of a DWC is 10 cm $\times$ 10 cm. A spatial resolution (the smallest spatial separation that can be measured) of 200 µm–300 µm can be achieved.[11] DWCs 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.

Further details (optional reading):

DWCs consist of an array of horizontal and vertical wires that are kept at high voltage, creating an electric field. DWCs are filled with gas (a mixture of argon and CO_2). Any ionising particle that passes through the chamber will ionise the atoms of the gas (i.e. free electrons from the atoms). The resulting ions and electrons are accelerated in opposite directions by the electric field across the chamber, causing a localised avalanche of ionisation. The electrons and ions induce an electrical signal in the horizontal and vertical wires. The wires are connected to a so-called delay line. Hence, two electric signals build up in the delay line, one from the horizontal and one from the vertical wires. 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 point where the first ionisation took place (i.e. where the particle passed through the DWC) can be determined.

Beam telescopes

A beam telescope can measure the 3D (three-dimensional) track of a particle. Knowing the track of a particle allows pointing to the source of the beam, and thus, the beam telescope is historically called "telescope", like the telescopes used in astronomy. A beam telescope consists of at least three detector planes, which are subsequently ordered along the beam axis. That is, beam telescopes can tell **where did a particle pass through the planes of the detector**. A telescope with six planes is visible in Figure 13.

Each plane consists of a 2D (two-dimensional) silicon pixel detector, similar to nowadays mobile phone cameras. Each silicon pixel detector can give the x- and y-coordinates of the position of a particle that passes through. Combining the positions from the different detectors, the 3D-track of the particle can be reconstructed. The resolution achievable by a telescope is usually in the order of a few µm. Compared to DWCs, telescopes have by far higher spatial resolution and provide more accurate tracking. However, each 2D silicon pixel detector of the telescope's planes only has an area of 2 cm $\times$ 2 cm.

A typical setup using beam telescopes has three planes before and three planes after a sample under test. With such a setup, one can conduct, for example, scattering experiments to learn more about the internal structure of a material. When the

[11] The unit “µm” represents a micrometre, one millionth of a meter.

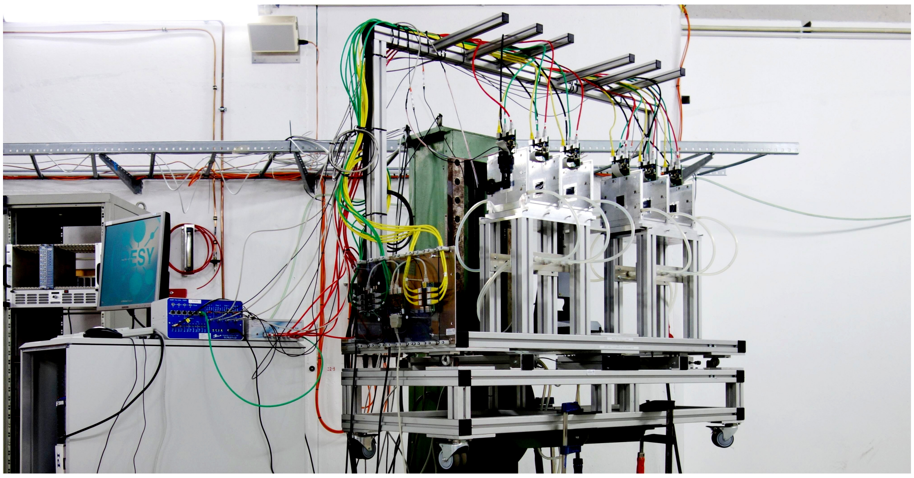


Figure 13: Beam telescope with six planes.

particles (i.e. the beam) interact with the material under test, they will scatter (i.e. move in different directions). Due to the high precision of the telescope's silicon pixel detectors, the scattering angles can be determined.

Further details (optional reading):

Silicon detectors are based on the creation of electron-hole pairs. If a high-energy particle passes through the silicon pixel detector, it will transfer some of its energy to the pixels through which it passes, creating electron-hole pairs. Since the silicon is held in an electric field, the electrons and holes move in opposite directions. The electrons may gain enough energy to free another electron (avalanche effect). Ultimately, they induce an electrical signal (see Basic principles of particle detection).

Neutron detectors

All of the above-described detectors available for your experiments are not sensitive to neutral particles. However, the WENDI detector is able to **detect neutrons** (see Figure 14). It is based on ionisation (see Basic principles of particle detection). There are no neutrons in the beam available for your experiments (see Beamlines). Yet, when the beam passes through a dense material, such as Tungsten, nuclear spallation will happen. In this process, neutrons are freed from the nuclei of the atoms of the material. The dose (which depends on the number and energy of freed neutrons) can be measured with the WENDI detector. The WENDI cannot react to individual neutrons. Nevertheless, one can indirectly draw conclusions about the number of freed neutrons per unit of time by measuring the dose of neutrons with the WENDI detector for a fixed amount of time. For example, one can compare different materials regarding their spallation efficiency (i.e. how many neutrons were freed from different materials in the same amount of time).

Figure 14: WENDI Neutron detector.

Further details (optional reading):

The WENDI detector is filled with gas, typically with Helium-3, and particles are detected based on ionisation. As you know from the Basic detection principles, the creation of electrically charged particles is necessary to induce an electrical signal. If the neutron detector is filled with Helium-3, a neutron can combine with a Helium-3 atom and transform into one Hydrogen-3 and one Hydrogen-1 atom (i.e., electrically charged particles). These can ionise the gas, resulting in the induction of an electrical signal (see Basic principles of particle detection).

BL4S detectors of type (2)

Scintillation detectors

A scintillation detector is a 1D (one-dimensional) particle detector based on scintillation (see Basic principles of particle detection). Scintillation detectors can give information on **whether a particle passed through the plane of the detector**. There are several scintillation detectors with different sensitive areas available for your experiments, from 1 cm × 1 cm to 10 cm × 20 cm. In addition, scintillation detectors can provide time information, that is, they can tell **when did a particle pass through the plane of the detector**. Thus, one exemplary use-case of scintillation detectors is Time-of-flight measurements. Knowing the time it took the particle to move from the first scintillation detector to the second scintillation detector, as well as the distance between the detectors, one can also calculate the speed of the particle. The distance between two scintillation detectors can be measured to an accuracy of 1 cm and the time to an accuracy of 200 ps (200×10^{-12} s).

Another exemplary use case of scintillation detectors is detecting the beam's halo (i.e. particles that move at some distance from the other particles in the centre of the beam).

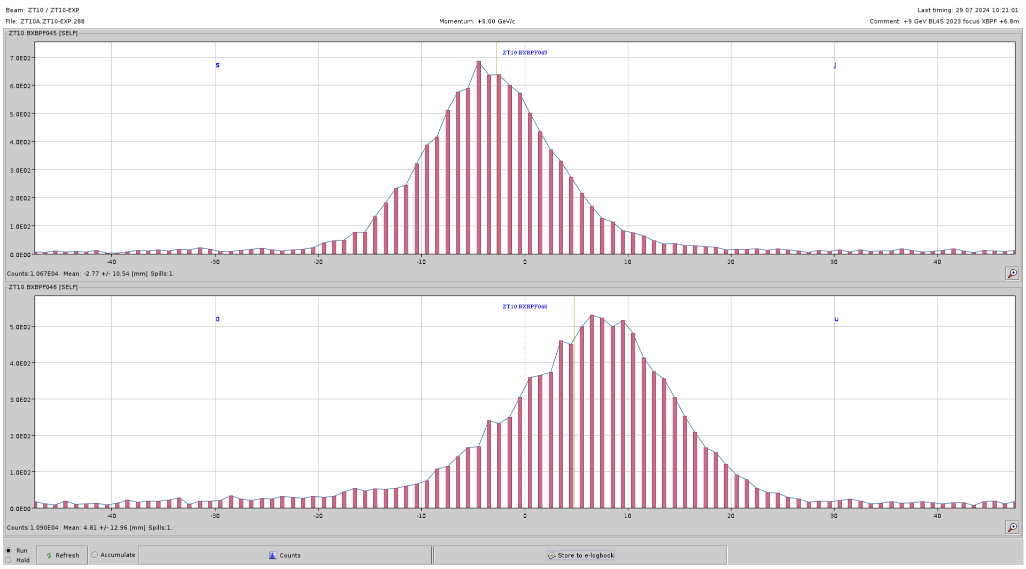


Figure 15: **Distribution of particles forming the beam.** The x-axis shows the position relative to the centre of the experimental area in mm. The y-axis shows the number of particles counted at this position. The upper plot shows the horizontal, and the lower plot the vertical particle count. In the bottom left corner of each plot is the total count of particles (10.7k for horizontal, 10.9k for vertical).

To understand better how the particles are typically distributed, you can have a look at Figure 15, which shows the distribution of the particles. One can see that there are quite a few particles at some distance from the other particles in the centre of the beam. These are the particles that form its halo. To detect the beam's halo, one can arrange, for example, four scintillators around the beam such that they form a hole for the centre of the beam to pass through (Figure 16). One can also use one scintillator with a hole. The opening of the halo detector can range from 1 cm to 15 cm. By detecting the particles of the beam's halo, one can decide not to further consider them for analysis or to flag them (i.e. to mark them as interesting for certain phenomena). For example, it is useful to flag particles that interacted with a material, and hence, scattered.

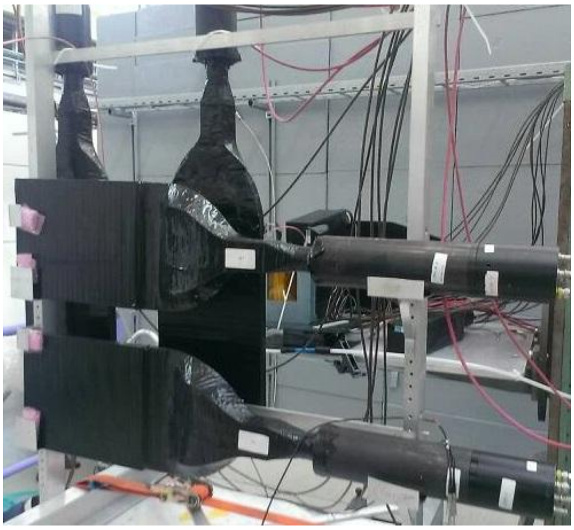


Figure 16: Arrangement of 4 scintillation detectors to detect the beam's halo.

Finally, scintillation detectors can be used to count particles. Moreover, two scintillation detectors measuring in coincidence can form the trigger, making sure that only particles that move through the full setup are considered.

Further details (optional reading):

When an electrically charged particle moves through a scintillation detector, it transfers some of its kinetic energy to the detector. An electron of the detector material absorbs some of the transferred energy and is, thus, at a higher energy level (i.e. the electron is in an "excited state"). The electron returns to its normal energy level ("ground state") by releasing the transferred energy in the form of a photon. This process is known as **scintillation.**[12] A scintillation detector consists of a scintillator

[12]Scintillation is an example of luminescence. You can learn more about the different types of luminescence here.

(i.e. a material that exhibits scintillation) and a device that converts the photons into an electric signal. This device can be a photomultiplier tube (which is usually the case for BL4S) or a silicon photomultiplier. A photomultiplier tube consists of a series of electrodes providing electric fields. When entering the photomultiplier tube, the photons emitted by the scintillator hit an electrode. The photon's energy is absorbed by an atom of the electrode, and hence, an electron is freed from the electrode. This process is known as the photoelectric effect. The freed electron gains kinetic energy (i.e. they become faster) because of the electric field provided by the electrodes. An electron can gain enough kinetic energy to free another electron when it hits the next electrode and so on. This process is called the avalanche effect and results in an amplification of the induced electrical signal.

Threshold Cherenkov detectors

A threshold Cherenkov detector is a 1D (one-dimensional) particle detector based on the Cherenkov effect (see Basic principles of particle detection). When a particle moves faster than light (i.e. photons) in a dielectric material (e.g. some gases, liquids or solids), photons are created in the material that free electrons, and ultimately, induce an electrical signal. The threshold Cherenkov detectors available for your experiments are gas-filled. Cherenkov detectors can give information on **what type of particle passed through the detector**. This is because, for Cherenkov photons to be created, a particle must travel at a speed greater than a certain threshold speed. The threshold speeds of different particles depend on the pressure and the type of gas. At CERN, two gas-filled Cherenkov detectors are available for your experiments. You can choose different gases and pressure values of the gas according to what particles you would like to detect. At a given momentum, you can distinguish between electrons, muons and pions by changing the pressure of the gas inside the detector. Identifying heavier (and therefore slower) particles (kaons or protons) is more difficult.

Further details (optional reading): Nothing is faster than the speed of light (i.e. photons) in vacuum (i.e. in a completely empty space). However, in dielectric materials, the speed of particles can be greater than the speed of photons in that material. When a charged particle passes through a dielectric material with a speed greater than the speed of photons, the material emits Cherenkov photons.[13] The dielectric material gets polarised when a charged particle passes through; that is, the atoms' electrons arrange differently. When the material returns back to its normal state, Cherenkov photons are emitted. However, the speed of the particle has to be greater than c/n, where n is the index of refraction of the material and c is the speed of light (i.e. photons), for this to happen.

Remember that you know the momentum of the particles because you choose it

[13] We recommend these two videos explaining the Cherenkov effect: video 1 and video 2.

(see Beamlines). The refraction index of a gas-filled Cherenkov detector, and hence, the threshold speed, can be changed by changing the pressure of the gas. Given that all the particles have roughly the same momentum but different masses, the particles have different speeds. Hence, different particles move faster than the threshold speed at different pressures, resulting in the creation of Cherenkov photons. Hence, you know which type of particle passed through the detector.

Lead glass calorimeter

A lead glass calorimeter is a 1D (one-dimensional) particle detector based on the Cherenkov effect (see Basic principles of particle detection and "further details" of Threshold Cherenkov detector above). A lead glass calorimeter can give information on whether a particle passed through the detector. In addition, it can provide information on the **energy of electrons, positrons, and photons** that pass through it. This is why they are called electromagnetic calorimeters. An electron, positron or photon hitting the calorimeter will produce a fully contained electromagnetic shower. During an electromagnetic shower, all the energy of the incoming particle is transformed into other particles via different processes, for example, Cherenkov photons are created. By measuring the energy of the created particles, the energy of the initial, incoming particle can be measured. 16 lead glass calorimeters are available for the experiment, each has a volume of 10 cm × 10 cm × 37 cm (Figure 17).

Figure 17: Stack of lead crystal calorimeters.

The energy resolution, σ_E, of the calorimeter is estimated, at energy E, as:

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

Further details (optional reading):

In the electromagnetic shower, all the energy of the incoming particle is transformed into other particles via different processes[14]. For example, some Scintillation photons are created, but many more Cherenkov photons. A lead glass calorimeter consists of a piece of lead glass (i.e. a material that emits Cherenkov photons among others) and of a device that converts the photons into an electric signal. This device can be a photomultiplier tube (which is usually the case for BL4S) or a silicon photomultiplier. The photomultiplier tube attached to the lead glass is specifically tuned to detect Cherenkov photons. A photomultiplier tube consists of a series of electrodes providing electric fields. When entering the photomultiplier tube, the photons emitted by the lead glass hit an electrode. The photon's energy is absorbed by an atom of the electrode, and hence, an electron is freed from the electrode. This process is known as the photoelectric effect. The freed electron gains kinetic energy (i.e. they become faster) because of the electric field provided by the electrodes. An electron can gain enough kinetic energy to free another electron when it hits the next electrode, and so on. This process is called the avalanche effect and results in an amplification of the induced electrical signal.

Availability of detectors

Type of Detector	CERN	DESY	Bonn
Scintillators	yes	yes	yes
Electromagnetic calorimeter	yes	no	no
DWC	yes	no	no
Cherenkov detector	yes	no	no
Beam Telescope	no	yes	yes
Neutron detectors	yes	no	no

Table 1: Detector availability

[14]For example, via pair-production or strong interactions with nuclei of the material

Glossary

Anti-protons	An anti-proton is the antimatter twin of a proton. Hence, it is a hadron made of the three anti-quarks: 2 anti-up and 1 anti-down. 15
Beam divergence	The particles of the beam will spread out while moving along their path. Thus, the diameter of the beam becomes bigger and bigger. 20
Beam halo	Some particles move at some distance to the other particles that form the center of the beam. These particles are called "beam halo". 20
Biological material	For example, living cells, human / animal tissue, bacteria, viruses, etc. 17
Boson and fermion	Particles can be categorized as bosons or fermions according to their intrinsic spin. Bosons have integer spin numbers, and fermions fractional spin numbers. For example, photons are bosons and electrons are fermions. 8
Bremsstrahlung	A photon produced when a charged particle is deflected by another charged particle. The deflected charged particle loses energy by emitting a bremsstrahlung photon. See also: Wikipedia: Bremsstrahlung. 11
Calorimeter	A detector that measures the energy of a particle. 7, 29
Cherenkov detector	A detector made from a dielectric material. When electrically charged particles move through this material with a speed greater than the speed of light (=photons) in that material, the material emits Cherenkov photons. More info: Wikipedia: Cherenkov detector. 6, 17

Coincidence module

A digital electronic module (essentially a logic "and") that provides an output signal when all input signals are active at the same time. 7, 8

Electromagnetic shower

An avalanche of particles created when a high-energy particle interacts with the material of a calorimeter. This process is called "shower" because the particles are produced both from the interaction of the initial particles with the material and from further interactions of the newly produced particles and so on. In an electromagnetic shower, incoming electrons, positrons or photons cause the creation of new bremsstrahlung photons and electron/positron-pairs. 29

Flux

Number of particles crossing a defined area (e.g. 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: $[\mathrm{Number}]/[\mathrm{L}^2 \cdot \mathrm{T}]$. 15

GeV

Electronvolt (eV) is a unit of energy used in particle physics. One electronvolt is defined as the energy gained by one electron accelerated by a potential difference of 1 V: 1 GeV = 1.6×10^{-10} Joule. The letter G stands for Giga, 1 GeV=1×10^{9} eV. 6

GeV/c

A unit of momentum used in particle physics. 6

GeV/c^2

A unit of mass used in particle physics. 1 GeV/c^2 = 1.783×10^{-27} kg, where c is the speed of light. 6

Ionising particle

A particle with enough energy to ionise an atom, that is, to free an electron from an atom. 23

Kaons

Kaons are hadrons, heavier than pions. They are made of two quarks: one strange quark (or antiquark) and one up or down antiquark (or quark). Kaons can be positively or negatively charged, or neutral, and within a characteristic time, they transform into other particles, typically into muons. 15

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. 6, 15

Momentum acceptance

The range of particle momenta that will be accepted and registered by a detector. For example, one could set a minimum momentum value, and hence, only particles with a momentum above this minimum value will be considered. 20

Muons

A muon, μ, is a particle similar to an electron but much heavier and not stable. That is, muons transform into other particles (with a characteristic half-life time). Typically, a muon transforms into an electron (or positron), an electron neutrino (or antineutrino), and a muon neutrino (or antineutrino). 15, 16

Nuclear spallation

This is a process in which neutrons are freed from the nuclei of a material when the beam interacts with the material. See also See also: Wikipedia: Spallation. 24

Pions Pions, π, are hadrons made of two particles: one up quark (or antiquark) and one down antiquark (or quark). Depending on the constituents, a pion can be positively or negatively charged, or neutral, π^+, π^-, π^0, respectively. Pions are not stable (with a characteristic half-life time). They typically transform into a muon (or anti-muon) and a muon neutrino (or muon anti-neutrino). 15

Proton A proton is a particle-system, consisting of one down-quark and two up-quarks. Protons are positively electrically charged. 15

Root A software to display and analyse physics data. We use it a lot in BL4S. 9

Scattering Scattering means that an incoming particle interacts with another particle in such a way that the incoming particle changes its direction of movement. There are several different types of scattering. For example, inelastic scattering can lead to the creation of new particles. 27

Scintillation detector A scintillation detector consists of a scintillator (i.e. a material that exhibits scintillation) and a photomultiplier (i.e. a device that converts the photons emitted by the scintillator into electrical signals). The size of the electrical signal is proportional to the energy of the initial electrically charged particle. For example, a particle with a really high energy will lead to a really high electric signal. 6, 17

Synchrotron A specific type of particle accelerator, in which the particles are accelerated and move along a circular path. The field strenght of the magnets, which make the particles move along a circular path, is synchronized to the increasing kinetic energy of the particles, that is, it becomes bigger with time during the accelerating process. See also: Wikipedia: Synchrotron. 11

Time-of-flight measurements Measuring the time a particle takes to move a certain distance. Time-of-flight (ToF) measurements provide information about the speed of the particle, and hence, other characteristic, such as momentum or particle type, can be deduced. 26

Tracking Measuring the trajectory of a particle. 6

Trigger The trigger identifies interesting interactions ("events") and instructs the computer to collect the data from all the detectors when there is an interesting event. 8