Beam and detectors

Beamline for Schools 2023

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 search the Internet. Wikipedia is usually a good starting point and provides very accurate and detailed information about scientific terms both in English and in your mother tongue.

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Glossary

Anti-protons An antiproton, also known as pbar, 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. 17

Beam divergence The spreading of the particles in the beam along their path. 14

Beam halo The cloud of particles surrounding the main beam in an accelerator. 14

Biological material Living cells, human / animal tissue, bacteria, viruses. 18

Boson Particles can be categorized as bosons or fermions according to their intrinsic spin. Bosons have integer spin numbers, and fermions fractional spin numbers. 12

Bremsstrahlung An electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle. See also: Wikipedia:Bremsstrahlung. 14

Calorimeter A detector that measures the energy of a particle. 10, 26

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. 10, 16

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. 10

Collider An accelerator that collides two beams which are travelling in opposite directions as in the LHC. 9

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. 26
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: $[\mathrm{Number}]/[\mathrm{L}^2 \cdot \mathrm{T}]$. 17–19
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 GeV = 1.6×10^{-10} Joule. The letters G stays for Giga, 1 GeV=1×10^9 eV. 9
GeV/c	A unit of momentum used in particle physics. 9
GeV/c^2	A unit of mass used in particle physics. 1 GeV/c^2 = 1.783×10^{-27} kg. 9
Ionizing particle	A particle with enough energy to knock out electrons of atoms or molecules. 22
Kaons	Kaons are hadrons, heavier than pions, and made of quarks of type up, down or strange. Kaons can be positevely, negatively charged or neutral, and within a characteristic time, they transform into other particles, typically pions. 17

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. 23

MKS units: Units expressed in meters, kilograms and seconds. 9

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, 18–20

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. 14

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). 17

Photomultiplier: A device that converts photons into electric signals. 10, 21

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 positevely, 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. 17

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. 17
Proton	A proton is a subatomic particle, with a positive electric charge. 9
Readout system	A combination of special electronics modules, computers and special software used to capture the signals of a detector, to digitize them and to store them in files. 10
Root	A powerful software framework for the display and analysis of physics data. 12
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). 22
Scintillation counter	A transparent material that emits light when penetrated by charged particles. 10, 21, 22
Synchrotron	A specific type of particle accelerator, in which the particles are accelerated and fly along a circular path. See also: Wikipedia: Synchrotron. 14
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. 25
Tracking	The measurement of the trajectory of a particle. 10, 26
Trigger	It identifies interesting interactions ("events") and instructs the computer to initiate the readout of the data from all the detectors. 11

Introduction

In 2023 there will be three winning teams. Two teams will perform their experiments at CERN and one team will be invited to DESY. The decision about which team goes where will be taken by the organizers of BL4S on the basis of the requirements of the winning experiments with respect to beam properties and instrumentation. Once the winners are selected, the organizers will make sure that each team will be assigned to the laboratory that best matches the requirements of their proposal.
In this document you will find details about the properties of the beams at CERN and DESY. Keep in mind that you cannot propose an experiment that requires a mixture of both beam properties. For what concerns the detectors and instruments that are mentioned in this document, you can assume that they are available at both institutes.

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 your 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 you suggest to overcome them.

Physics experiments at particle accelerators

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** and allows you to perform experiments with different kinds of charged particles.

Please note that the particle beam at CERN does contain neutral particles (neutral pions and kaons). In addition, the interaction of the beam with a target may produce other neutral particles (neutrons, neutrinos). Our detectors, however, are not able to measure any properties of neutral particles. You must only use charged particles for your experiment, the detection of neutral particle is not possible or very hard.

Commonly used units

In high-energy physics, the units for energy, Momentum and mass are eV, eV/c and eV/c^2, 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 GeV = 1×10^9 eV = 1.6×10^{-10} Joule, 1 GeV/c^2 = 1.783×10^{-27} kg. For comparison, the maximum energy of the Proton beam at the LHC is 6800 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.

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

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?"**.
- Magnets **modify the trajectory of charged particles according to their electric charge and their momentum**. Therefore, they can separate particles with opposite charges or, if combined with tracking detectors, they give information about the particle momentum [1].

All these detectors are *electronic* detectors: when a particle passes through them, an analogue electrical signal (for example a voltage, current or charge) is produced in different ways. For example, in a Cherenkov detector or a scintillator, light is emitted when a particle passes 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 $\sim$10 ns to $\sim$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

[1] Bending magnets have to be used together with tracking detectors. The bending angle of a particle that passes though a certain magnetic field is inversely proportional to its momentum.

a Cherenkov detector that they had conceived. To do so, the incoming beam, coming 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 that the team wanted to characterize, and it crosses another pair of trackers. The four trackers together indicate the position of the particles and allow a good alignment of the detector under investigation. Finally the beam hits a last scintillator, that is used to generate the Trigger signal for the data acquisition.

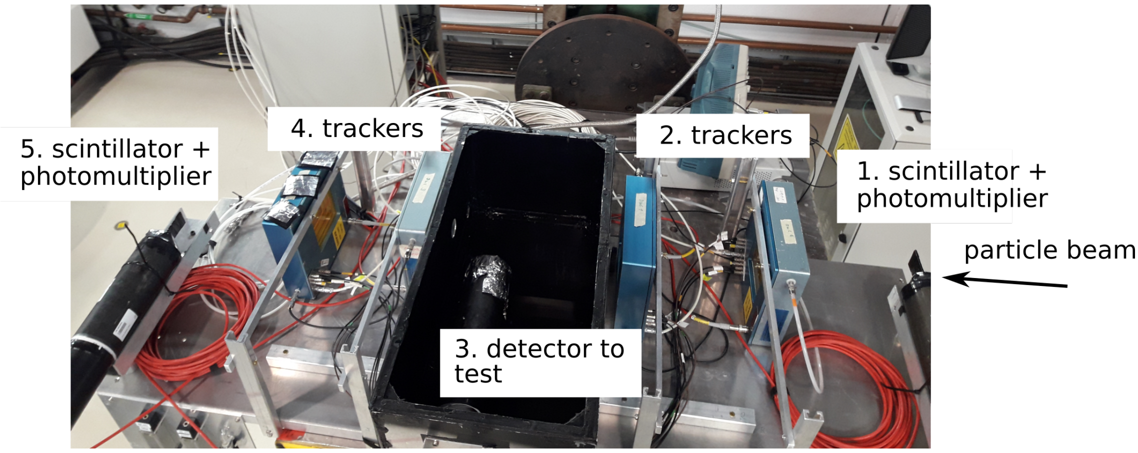

Figure 1: The experimental setup of one of the winning teams of the 2021 edition of the competition, the "Teomitzli team". The particle beam comes from the right, it first crosses a scintillator (1.), then 2 trackers (2.), it goes through the detector under test (3.), it crosses a second pair of trackers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

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.

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

Beam lines

In beam lines, particles are extracted from a particle accelerator and beams are prepared and optimised to be used in fixed-target experiments. The particle extraction and the beam preparation is done using different instruments, each having a specific role: particle type and energy selection, focusing, etc. This chapter starts with a description of two important devices used to prepare beams, bending magnets and collimators, later the beam properties at DESY and CERN are described in detail.

Bending magnets

Bending magnets[3] are used in beam lines 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.

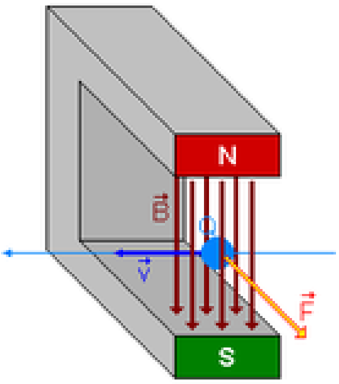

Figure 2: A dipole magnet with the vertical magnetic field and a charged particle moving horizontally into the field. The force is perpendicular to the magnetic field vector and the velocity vector, deflecting the charged particle horizontally. Image source: Wikipedia.

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

Collimator

A collimator is a tool used to filter a particle beam. Typically collimators are used to define the Momentum acceptance, Beam divergence and to 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 is the flux. Don't worry too much about the details of these collimators. The BL4S support scientists will set them up for you.

Beam properties at DESY

The beam available at DESY is a pure electron or position beam with energy ranging from 1 to 6 GeV/c. The particle accelerator is called DESY II and it is a Synchrotron accelerating electrons up to an energy of 6.3 GeV.

Beam production

The beam production at the DESY II Test Beam Facility is sketched in Figure 3.

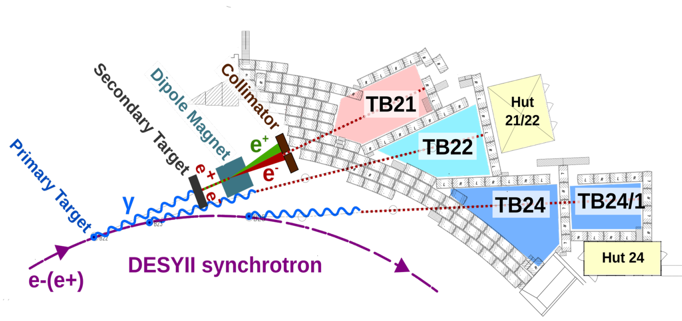

Figure 3: Sketch of the test beam production at DESY II.

Inside of the DESY II accelerator, Bremsstrahlung photons are produced by putting a target, called primary target, into the beam. The primary target consists in a 7 µm thick carbon fibre. The photons fly towards a target, also called conversion target, where electron / positron pairs are produced in a few mm thick metal plates. The electron/positron pairs pass a dipole magnet with a collimator behind. By steering the magnetic field in the dipole and the collimator opening, the momentum and the momentum spread of the resulting electron or positron beam in the following test beam area can be chosen to any values between 1 and 6 GeV/c. The resulting beam consists of mainly single electrons or positrons at rates of up to several kHz, depending on chosen momentum. To summarize, by tuning the magnetic field and the collimators placed after the magnet, one can choose the properties of the secondary particle beam, available for the experiments:

- The particle type: electrons or positrons.
- The particle momentum: any value between 1 GeV/c and 6 GeV/c.
- the momentum spread: a typical value for the momentum spread is around 0.15 GeV/c.

The rate of particles in the beam can reach several kHz, depending on the momentum. As the beamline provides mostly one particle at a time, it lends itself well to experiments that focus on effects that can be seen with individual particles. Experiments that require a high number of particles (e.g. the irradiation of electronics) are more easy realize at CERN.

Beam composition and intensity

The amount of particles in the beam depend on the primary target, the selected momentum and the polarity. Figure 4 shows the typical particle rates available in the beam area. It is not possible to have a beam of photons. The negative (positive) beam contains negatively (positively) charged electrons or positron. The particles of the beam are relativistic. This means they are moving at almost the speed of light. The beam provided by DESY II is not using bursts or spills like at the PS at CERN (see next paragraphs), instead within a 80 ms cycle there are continuously particles delivered. The length of the period depends on the selected energy with the period being longer the lower the desired particle energy is. The available rates are up 10 kHz. The beam has, more or less, a round cross section. The beam spot size is driven by the collimators and has a typical dimension of 2 x 2 cm when entering the beam area. The further away the beam is from the entrance window, the wider it gets. In addition to the electrons and positrons generated, the amount of background particles (photons, muons, neutrons) is negligible.

The Test Beam Area at DESY

The Beamline for Schools experiment takes place in one of the test beams, which have an area of about 5 m by 10 m, where the available equipment can be laid out according to the needs of your experiment. Also depending on the area, there are some fixed installations like a big magnet.

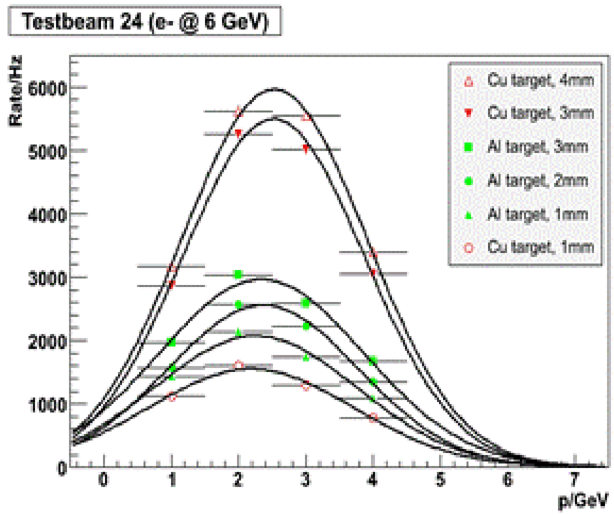

Figure 4: Typical rate of the single electron beam in test beam area TB21 depending on the selected particle momentum. Rates are shown for different converter target types and thicknesses.

The T9 Beam Line at CERN

At CERN, the BL4S experiments take place in the T9 beam line of the CERN Proton Synchrotron (PS). The experimental area where the T9 beam line is located 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, that accelerates protons up to an energy of 26 GeV.
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 beam line. These beams are known as "secondary beams".

Beam Properties

The secondary beams available at the PS include different types of particles having an energy ranging between 0.2[4] and 15 GeV. Bending magnets, collimators and two Cherenkov detector placed at the entrance of the experimental area are used to sep-

[4] Please 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.

arate and identify the particle species.
Figure 5 and 6 show the composition of positive and negative beams respectively [5]. It 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 other particles along their path to the test beam area. For example Pions transform into Muons within a characteristic half life time of $\sim$ 26 nanoseconds. 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 pure 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 6 shows that a beam of negative particles having a Momentum of 4 GeV contains $\sim$450 antiprotons, $\sim$10000 Electrons and Kaons and $\sim$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. The ratio of particles present in the beam as a function of the beam Momentum with the hadron rich target is shown in Figure 7 (for positive particles) and 8 (for negative particels). Keep in mind that these plots complement those shown in Figures 6 and 5, and they have been produced after a recent renovation of the beam.
Furthermore, there is also the possibility to have a very pure electron beam with an energy ranging from 0.5 GeV to 4 GeV. [6].
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

[5] Please 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.

[6] To create a pure electron/positron beam the secondary beams of charged particles are deflected away with two bending magnets and only the neutral gammas rays (Gamma rays are photons with energies above 0.5 GeV) 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%

further away the beam is from the focal place, the larger the diameter. The position of the focal point can be adjusted.

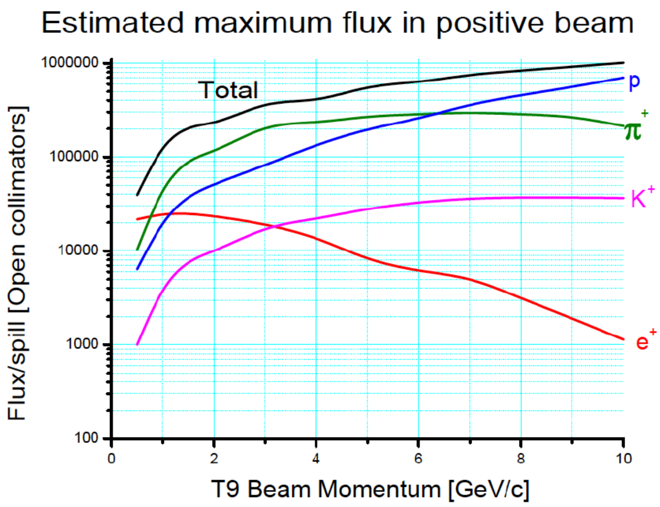

Figure 5: The Flux of positive particles present in the beam as a function of their Momentum. Please note that the flux is calculated over a time of 400 ms, and the most important information that you should retain from this plot is relative intensity of particles of different species.

The T9 test beam areas

T9 has a size of about 5 m × 10 m, ans the equipment can be laid out according to your experiment's needs (see figure 9).

Additionally, it may be possible to install devices that are brought by your team to the experimental area[7]. 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 (e.g. wood) is not possible for safety reasons. It is also not possible to expose any Biological material to the beam.

Take-home messages about the beam:

- The beam at DESY is a pure electron or positron beam with energy ranging from 1 GeV and 6 GeV. At this energy the particles are relativistic.

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

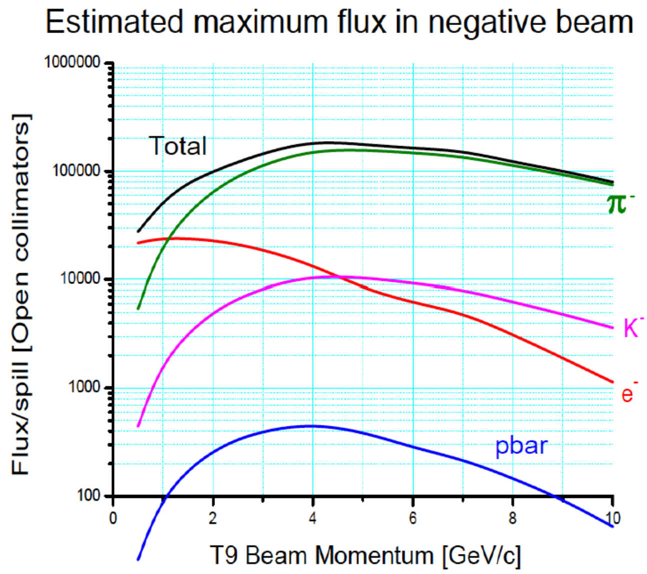

Figure 6: The Flux of negative particles present in the beam as a function of their Momentum. Please note that the flux is calculated over a time of 400 ms, and the most important information that you should retain from this plot is relative intensity of particles of different species.

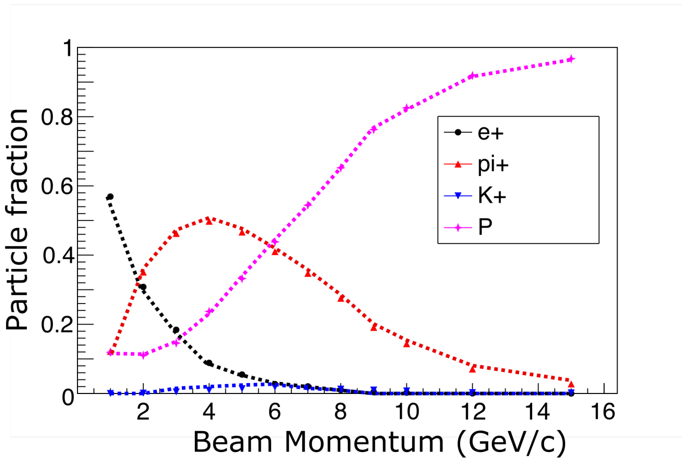

Figure 7: The ratio of positive particles present in the beam as a function of their Momentum. Please note that ratio is a relative value.

- The beam at CERN contains protons, electrons, positrons, antiprotons, kaons, pions, and muons. The particle energy ranges between 0.2 GeV and 15 GeV.

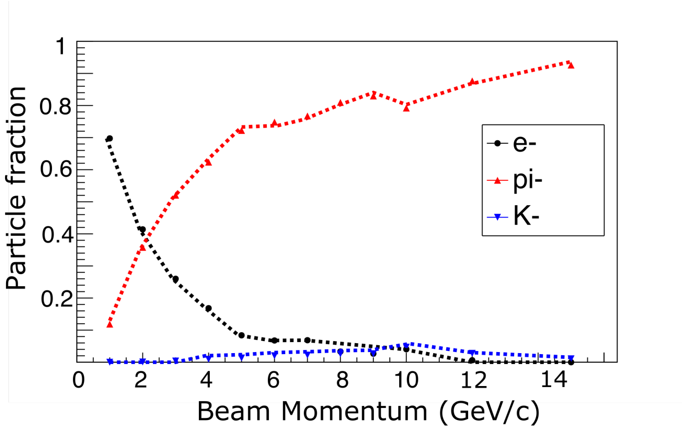

Figure 8: Ratio of negative particles present in the beam as a function of their Momentum.

At this energy, 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 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.
- Both at CERN and DESY the beam spot size at the focal point is round with a diameter of 2 cm.

Figure 9: The PS T9 testbeam area with the experimental setup of two of the three winning teams of the 2022 edition of the competion.

The BL4S detectors

Scintillation counter

A scintillator is a material that produces scintillation light, a property of luminescence, when excited by ionizing radiation[8]. 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 effect [9]. 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).

[8]You can watch a simple animation here.

[9]The extraction of an electron from a material hit by photons

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 10) 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.

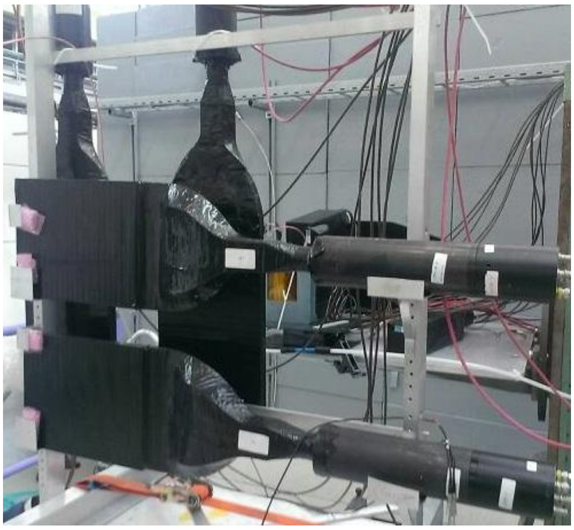

Figure 10: A Halo counter.

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 a signal takes to travel through it. The chamber is filled with gas (a mixture of argon and CO_2). Any Ionizing particle that passes through the chamber will ionize 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 cm × 10 cm and position resolutions (the smallest spatial separation that can be measured) of 200 µm–300 µm 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 µm and an active area of 40 cm × 40 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.

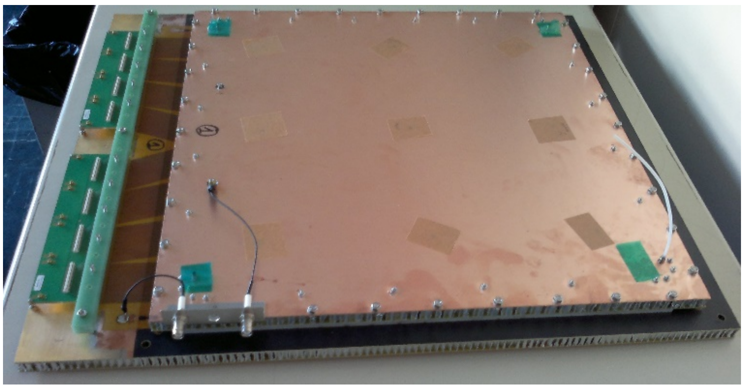

Figure 11: MicroMegas detector.

Beam telescopes

A beam telescope (six telescopes are visiblein Figure 12) can measure the track of a beam particle with high precision. Knowing the track of a particle allows pointing to the source of the beam - thus, it is historically called telescope as the telescopes used in astronomy. The resolution achievable by a telescope is usually in the order of a few µm.

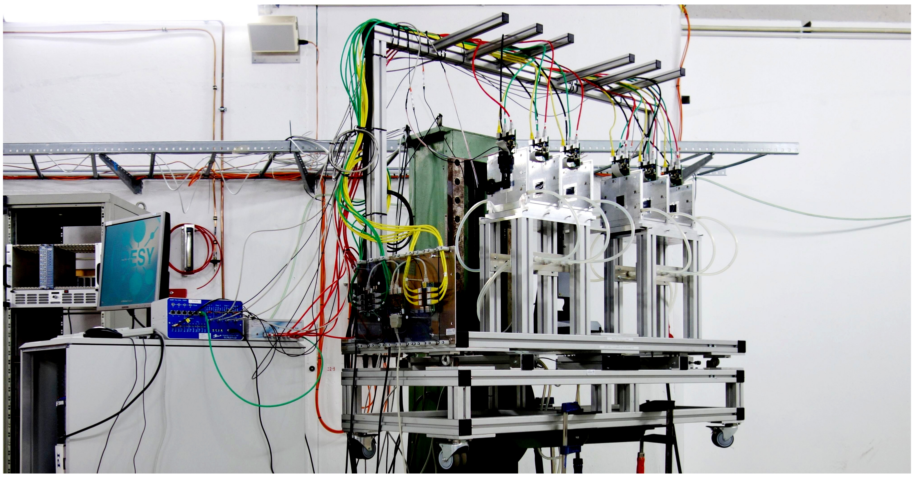

Figure 12: Beam telescope detectors. Six telescopes are visible in the figure.

A beam telescope consists of at least three planes which are subsequently ordered along the beam axis. Each plane has a sensitive silicon pixel chip, similar to nowadays camera chips in mobile phones. If a high energetic charged particles will go through the chip, it will produce a signal in certain pixels of the sensor. Knowing the positions in the pixel matrix in each telescope plane, the track of the particle can be identified.

A typical application is having three planes before and after a sample under test.

When the particles of the beam interact with a target they will scatter. Due to the high precision of the telescope sensors, the scattering angle can be determined. Thus, beam telescopes work as a camera which uses charged particles like electrons, instead of photons (light). Compared to the DWC and the MicroMegas detectors, telescopes have by far the highest special resolution and provide the most accurate tracking. The disadvantage is that the sensors in the telescope only have a surface of $2\,\mathrm{cm} \times 2\,\mathrm{cm}$.

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 (200×10^{-12} 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 [10]). 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 pre-selected, 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

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

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. Identifying heavier particles (Kaons or Protons) is more difficult.
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.

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 cm $\times$ 10 cm $\times$ 37 cm (Figure 13).The energy resolution, σ_E, of the calorimeter is estimated, at energy E, as:

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

Additional equipment

The BRM dipole magnet at DESY

At DESY, a large dipole magnet is available. It is a normal conducting dipole, called Big Red Magnet (BRM), with a field up to 1.35 T installed in area TB21 (see Figure 14). It has an integrated length of about 1 m and an opening that is about 1.5 m wide and 0.35 m high.

Magnet at CERN

Under certain conditions it is possible to install a dipole magnet in the T9 area. We are currently clarifying all the details. Please contact us is if you need a magnet in order to realize your experiment.

Figure 13: Stack of lead crystal calorimeters.

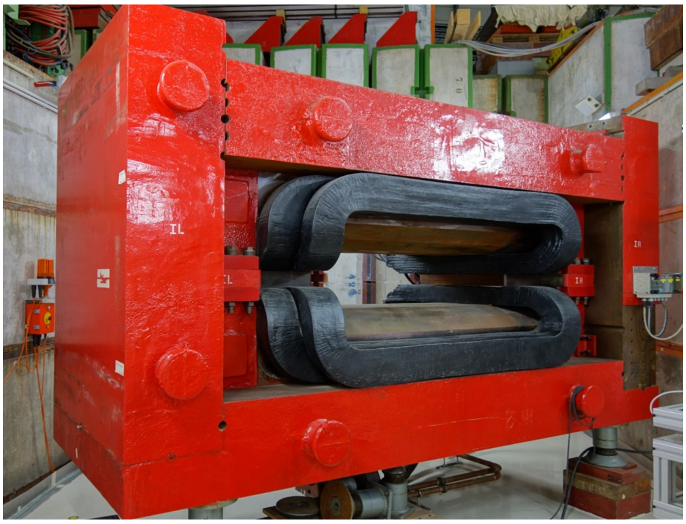

Figure 14: BRM, 1.35 T dipole magnet

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 and DESY. We do not expect you to design the Readout 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.