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Introducing modern particle detectors in the classroom: a slice-by-slice overview

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Abstract

This paper aims to provide a basis for teachers interested in bringing modern particle detectors into their classrooms. In particular, it gives an overview of the basic principles of modern particle detectors, linking them to concepts that are already a part of the curriculum. In addition, it explains the essential detector components present in all detector systems, and how the information they provide leads to particle identification. By highlighting relevant classroom resources, this paper serves as a valuable guide for teachers seeking to include modern particle physics in their teaching, and to set it within interesting and relevant contexts.

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1. Introduction

Particle detectors are essential to particle physics research as they are used to detect and identify the particles that are produced during particle collisions. In a particle accelerator, 'bunches', consisting of billions of particles, are accelerated to very high speeds, close to the speed of light. These bunches travel in opposite directions and are then made to collide at the centre of particle detectors. During each collision, many new particles are produced, and these can be detected as they travel outwards from the collision point, through the detector. Particle physicists study the properties of these particles in order to confirm or disprove their theoretical predictions. This helps them to answer some of the most fundamental questions of humankind, such as *'What are we made of?'* and *'How did the universe begin?'*

Although particle detectors are complex machines, the basic principles underlying detection are the same across all detectors, and they include many concepts covered in upper secondary school physics lessons (16–18 year olds) (e.g. energy, momentum, ionisation, electromagnetism). Therefore, teaching about particle detectors provides the perfect opportunity to bring modern physics into the classroom, and showcase the everyday applications of current research, as recommended in previous studies (Kranjc Horvat *et al* 2022). The importance of teaching particle physics is also emphasised in the 2020 European Strategy for Particle Physics, which states that: 'The particle physics community should work with educators and relevant authorities to explore the adoption of basic knowledge of elementary particles and their interactions in the regular school curriculum' (European Strategy Group Collaboration 2020).

In this paper we will first focus on the basic principles of particle detection. Next, we will describe the main components of a typical detector for particle collision experiments, and finally we will describe how the information we gather helps us to identify the particles. In addition, we will highlight relevant curriculum links and educational resources to support teachers in introducing modern physics research in their classrooms.

2. Detection—How do we know that a particle has travelled through the detector material?

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, as shown in figure 1.

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 (Fabjan and Schopper 2020). 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

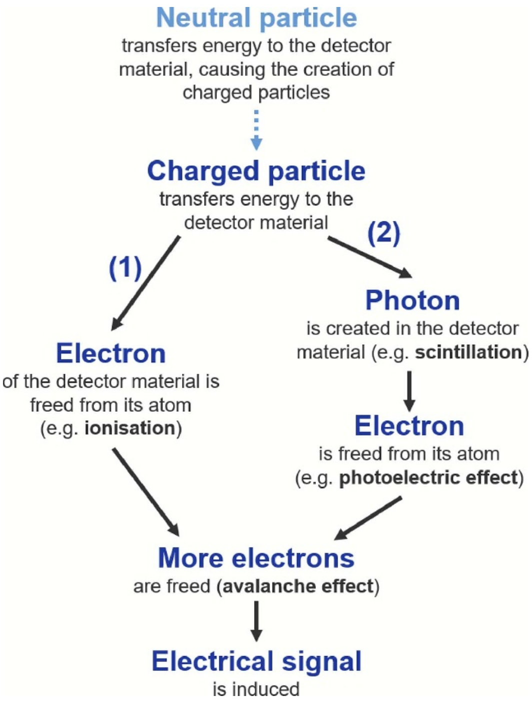

Figure 1. Illustration of the two main ways in which a particle can be detected.

electron of the gas gains the transferred energy and is, thus, freed from its atom, leaving an ion. This process is known as **ionisation** (Hilke and Riegler 2020).

The gas is held between a cathode and an anode, which create an electric field. As the electrons and ions have opposite electric charges, they move in opposite directions. 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 (Lutz and Klanner 2020).

(2) The electrically charged particle creates photons (e.g. scintillation) that subsequently free electrons (e.g. photoelectric effect): An electrically charged particle transfers some of its kinetic energy to a detector, for example a scintillator (Lecoq 2020). An electron of the detector material absorbs some of the transferred energy and is, thus, at a higher energy level ('excited state'). The electron then releases this transferred energy in the form of a photon and returns to its normal energy level ('ground state'). This process is known as **scintillation**[6]. At the end of the detector, the created photon hits a metallic surface and is absorbed by an electron, causing this electron to be ejected. This is known as the **photoelectric effect** (Bichsel and Schindler 2020).

Whether the electron is freed (1) directly by the electrically charged particle in a gas detector or semiconductor, or (2) indirectly via a photon in a scintillator, many more electrons must be freed in order 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 (Fabjan and Fournier 2020, Hilke and Riegler 2020, Lutz and Klanner 2020). 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 (Radeka 2020). This is the **electrical signal** that we read out.

3. Identification—How do we know what type of particle it was?

When accelerated particles collide, their total collision energy transforms into hundreds or even thousands of new particles, which move in all directions. Collision energy is the sum of the energy associated with the colliding particles' masses (in accordance with Einstein's formula, $E=mc^2$) and their total kinetic energy. To understand what is happening in a single collision, each produced particle needs to be identified by recording its trajectory and measuring its momentum and energy. To achieve this, modern particle detectors consist of several sub-detectors, arranged in layers around the collision point, similar to the layered structure of an onion.

From the hundreds of different particles that are produced during these collisions, most of them are extremely short-lived, and thus, will transform into other particles before reaching the first detector layer. We are unable to detect these extremely short-lived particles directly.

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[6] There are also other processes by which a photon can be created, e.g. bremsstrahlung, transition radiation, and Cherenkov radiation.

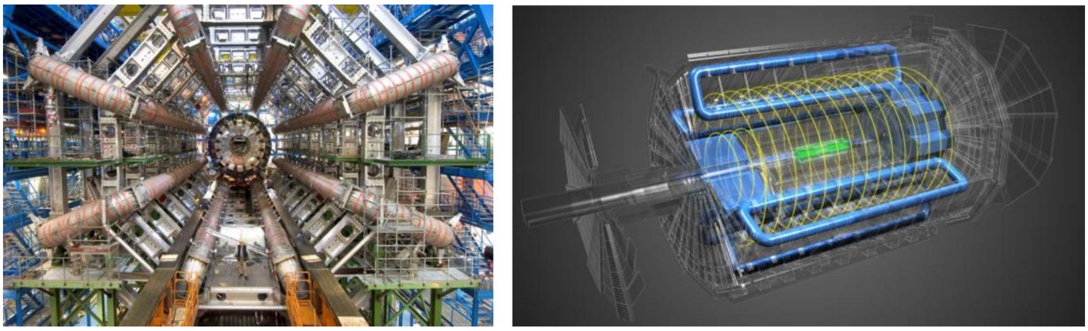

Figure 2. Left: ATLAS' magnet system consists of one large toroid magnet (whose eight electromagnets are visible in the photograph), two smaller toroid magnets on each side of the detector, and a solenoid magnet in its centre (Reproduced from [Installing the ATLAS calorimeter]. CC BY 4.0.) (https://cds.cern.ch/record/910381). Right: The magnetic field lines of the toroids (yellow) and solenoid (green) (Reproduced with permission from [ATLAS Detector Schematics]) (https://cds.cern.ch/record/2777214/files/?ln=en).

However, we can detect the particles that they ultimately transform into, which allows us to infer their existence. The particles we can detect are stable particles or those with a sufficiently long lifetime: electrons, muons, photons, protons, neutrons, kaons and pions (and their antiparticles) (Griffiths 2008). Their differences in mass, charge, and the way in which they interact with the various sub-detectors are key to their identification.

The rest of the paper will focus on the layers of a detector that are necessary to identify a particle, namely the magnet system(s), the inner tracking system, the calorimeters and the muon system.

3.1. Main detector components

3.1.1. Magnet system(s). Magnets are not actually detectors themselves, but they are an essential component of the particle detection process as they help to determine the electric charges and momenta of the produced particles. When an electrically charged particle travels through a magnetic field, a force acts on it, commonly referred to as the Lorentz force. For a particle moving at an angle to the field, this results in a curved motion. The magnitude of this force depends on four quantities: the particle's electric charge, the particle's relativistic momentum, the strength of the magnetic field, and the angle between the direction of movement of the particle and the orientation of the magnetic field. The higher the momentum, the less the particle's trajectory curves, and two particles with opposite electric charges curve in opposite directions. Therefore, by measuring the curvature of the charged particle's track (with the help of a sub-detector called the inner tracking system, presented below), we can determine its electric charge and momentum.

During a particle collision, the produced particles have a range of momenta. To observe a measurable bending of the trajectories of high momentum particles, the magnetic field needs to be very strong and the detector needs to be very large. As an example, the complex magnet system of the ATLAS detector (one of the four detectors at the Large Hadron Collider, or LHC, at CERN) is 26 m long and 20 m in diameter and uses electromagnets with large electric currents. A photograph of the ATLAS magnet system and a schematic of its magnetic field lines are shown in figure 2.

3.1.2. Curriculum links and classroom resources. The use of magnetic fields in particle detectors can be explained through the basic principles of electromagnetism. A three-part mini-series on this topic, entitled Electromagnetic Adventures, is available as part of the CERN-Solvay Education Programme (https://solvay-education-programme.web.cern.ch/online-course). In addition, multiple simulation platforms can be

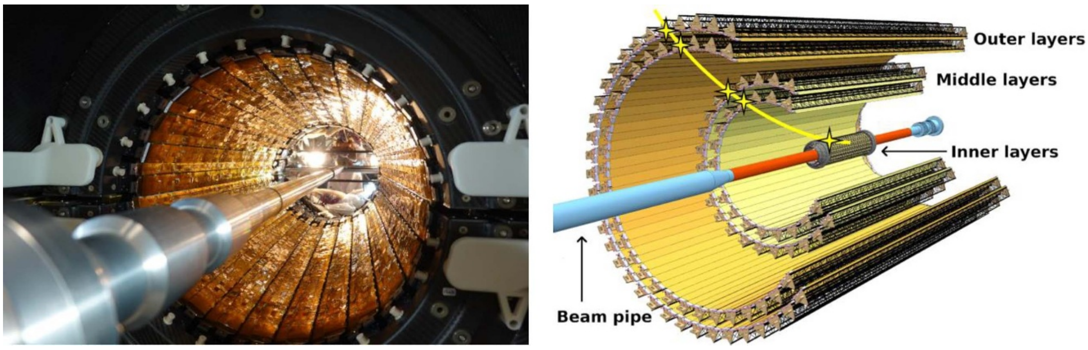

Figure 3. Left: Outer layers of the inner tracking system of the ALICE detector being installed around the beam pipe (Reproduced with permission from [ALICE ITS Outer Barrel Installation]) (https://cds.cern.ch/images/ALICE-PHO-ITS-2021- 001-32). Right: The inner tracking system. The yellow line and stars (added by the authors) represent a particle interacting with the pixel detector layers (Reproduced with permission from [Commissioning of the new ALICE Inner Tracking System]) (https://cds.cern.ch/record/2717344/plots).

found online (e.g. www.golabz.eu/lab/charge-in-magnetic-field; www.golabz.eu/lab/the-trail-behind-a-charged-particle-moving-in-a-magnetic-field). These resources help students to explore the behaviour of a charged particle in a magnetic field, by manipulating different physical parameters.

To visualise the magnet system of the ATLAS detector in three dimensions, students can build their own model using everyday materials (https://scoollab.web.cern.ch/atlas-magnet-model), or print a model using a 3D printer (Woithe *et al* 2020).

3.1.3. Inner tracking system. While the magnet system is a crucial component of any particle detector, magnets only help to *curve* the particles' trajectories. To actually measure these curved tracks, magnet systems need to be complemented by the inner tracking system, which is the first set of detector layers around the collision point. This system is designed to provide critical information about the collision, for example the exact location of the interaction point and where the short-lived particles transformed. Additionally, it helps to measure the curvature of the trajectories of all electrically charged particles in order to determine their momenta. Neutral particles, such as neutrons and photons, will not leave a trace here, but will be detected in a subsequent layer, the calorimeters.

There are several challenges to tracking. Firstly, since we are interested in measuring many different particle properties in subsequent detector layers, the inner tracking process should influence particles as little as possible. Secondly, position measurements need to be extremely precise, in the order of a few micrometres. Thirdly, to reconstruct a track and determine its curvature, many position measurements are required for a single particle.

Currently, the best solution to tracking involves many thin layers of silicon (a semiconductor detector material; see figure 1, basic principles), arranged around the collision point. Each layer consists of billions of tiny tiles called pixels, with the size of each pixel being comparable to the thickness of a human hair (tens of micrometres). Since silicon pixel detectors are very expensive, they are usually placed only at the innermost part of the detector system. After the silicon pixel layers, either multiple layers of semiconducting material, arranged in larger strips, or big gaseous detectors can be used to complement the silicon pixel detectors and provide sufficient information to reconstruct the particle tracks (Stapnes 2007).

The biggest silicon pixel detector ever built is that of LHC's ALICE experiment, shown in figure 3. This consists of 12.5 billion pixels, each 30 × 30 micrometres in size.

3.1.4. Curriculum links and classroom resources. Even though inner tracking systems are complex, much of their technology relies on the basic principles of ionisation and semiconductors. Silicon pixel detectors, which are used in every modern inner tracking system, are a fantastic example of the many applications of semiconductors and

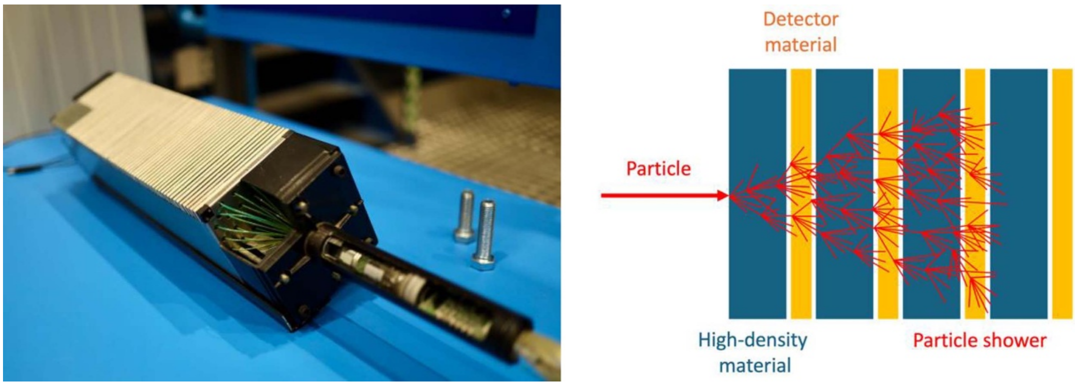

Figure 4. Left: A part of the electromagnetic calorimeter of LHCb. The sandwich-like structure and the fibres which transport the signal from the scintillators are visible (Reproduced with permission from [Electromagnetic and hadronic calorimeter in the LHCb exhibition]) (https://cds.cern.ch/record/2883609). Right: A particle entering the sandwich-like structure of the electromagnetic calorimeter and causing a particle cascade.

their properties. In the framework of tinkering projects, students can assemble their own low-cost silicon detector using a photodiode as a single pixel (https://scoollab.web.cern.ch/diy-particle-detector).

Pixel detectors have a wide range of applications in our everyday lives, which can provide a topic for discussion in the classroom. For example, all smartphone cameras contain a thin layer of silicon pixels, which convert photons into electrical signals. In addition, silicon pixel detectors are used in advanced Computed Tomography scanners for medical imaging, and are also used by astronauts to measure the radiation levels they are exposed to (https://medipix.web.cern.ch/space-dosimetry; https://home.cern/news/news/knowledge-sharing/timepix-cerns-galleries-moon).

3.1.5. Calorimeter(s). The word ‘calorimeter’ has the same latin root as the energy unit ‘calorie’, which indicates that this layer measures the energy of the particles. While the inner tracking system aims to influence the particles as little as possible, the calorimeter is designed to interact with them as much as possible, in order to stop them entirely.

To stop any particle, the particle’s total energy (its kinetic energy and the energy associated with its mass) must be transferred to the detector material. During this process, the original particle’s total energy can transform into new particles with lower energies, which in turn transform into more particles, in a process called a particle cascade. According to the principle of energy conservation, the energy of the original particle is equal to the sum of the energies of the new particles. In such cascades electrically neutral particles cause the creation of electrically charged particles in the detector material, which can be detected (see figure 1, basic principles).

To measure the total energy of a particle, the structure of a calorimeter is usually sandwich-like, involving two alternating materials, as shown in figure 4, the electromagnetic calorimeter of LHC’s LHCb experiment. One is a high-density material (e.g. steel or lead), in which the particle has many opportunities to interact and produce new particles. The other is the detector material, in which the energy of these produced particles is measured via scintillation (e.g. using plastic scintillators) or ionisation (e.g. using a volume of noble gas); see figure 1, basic principles. There are also detectors which combine the stopping and detecting layers into one material, for example by using high-density lead tungstate crystals.

To measure the energy of all particles, a detector typically includes both an electromagnetic calorimeter and a hadronic calorimeter.

The electromagnetic calorimeter detects the energy of all particles that interact electromagnetically, i.e. all electrically charged particles and photons. However, only electrons, positrons (the antiparticles of electrons) and photons are fully stopped in this detector layer. When high-energy electrons and positrons interact with the calorimeter, they emit so-called bremsstrahlung radiation in the form of high-energy photons. When the photons (either original or bremsstrahlung) interact with matter, it can result in a cascade of interactions; where the photons transform into electron–positron pairs, which emit bremsstrahlung photons, which transform into electron–positron pairs, and so on. A schematic illustrating this kind of cascade can be seen in figure 4 (right). The particle cascade ends when all particles have been transformed into electrons or photons with low enough energies to be absorbed by the detector material. During the stopping process, the energy of these particles is measured through the principles of scintillation or ionisation, as described above in figure 1.

In contrast, the hadronic calorimeter measures the energy of particles that interact hadronically with its material, i.e. hadrons (e.g. protons, kaons, pions). This interaction is more complex than that of electrons, positrons and photons. The hadrons interact with the nuclei of the atoms of the calorimeter, which can result in the production of many different particles, such as protons, Helium nuclei, neutrons, kaons or pions. These particles then initiate further particle cascades, with each new particle having lower energy. These particles are eventually absorbed by the detector material with their energy being measured in a similar way to the electromagnetic calorimeter.

3.1.6. Curriculum links and classroom resources.

Scintillators (a type of calorimeter) are used in a medical diagnostics technique called Positron-Emission Tomography (PET). More about the physics of PET, and how it can be used in practice, can be learned through a digital learning module (https://digital-learning-modules.web.cern.ch/pet-digital-learning-module). The physical process of scintillation is one of multiple ways in which light is created, as demonstrated in one of the CERN-Solvay Education Programme DIY Experiments Videos (https://solvay-education-programme.web.cern.ch/diy-experiments-videos).

In the context of thermodynamics, a different type of calorimeter is often used to determine the heat capacity of an object or food substance, for example a chocolate bar (www.phywe.com/experiments-sets/university-experiments/heat-capacity-of-metals_10675_11606/). Although the thermodynamic calorimeter uses different measurement principles to those found in particle detectors, the two can be linked by the concept of energy which appears in different forms. In the thermodynamic calorimeter, the microscopic movement of the object's particles is measured as thermal energy, whereas in the case of the particle detector calorimeter it is the energy of individual particles that is measured.

Since a particle detector calorimeter aims to measure the energy of particles by stopping them entirely, it essentially works as a particle shielding device. In the context of radiation protection, students can consider which materials work as protection for each type of radiation. Classroom demonstration instructions for the stopping of beta and gamma radiation are available by IOPSpark (https://spark.iop.org/beta-radiation-range-and-stopping; https://spark.iop.org/gamma-radiation-range-and-stopping).

3.1.7. Muon system.

Muons and antimuons are elementary particles, similar to electrons and positrons, but 207 times more massive (Nagamine 2003). Particle physicists typically use the word muons to refer to both muons and antimuons, as we will do for the rest of this section.

High-energy muons only come from transformations of heavy particles, therefore their identification and precise momentum measurement are crucial to the search for new phenomena in proton–proton collisions (Crane 2021). Muons have a relatively long lifetime and lose very little energy when passing through the detector material. As such, they are the only electrically charged particles that can travel through the whole particle detector without being stopped or transforming into other particles. Therefore, particles detected in the outermost layers of the detectors are almost exclusively muons, hence the name muon system.

The main purpose of the muon system is to accurately determine the momentum of muons. Muon systems typically measure muon tracks

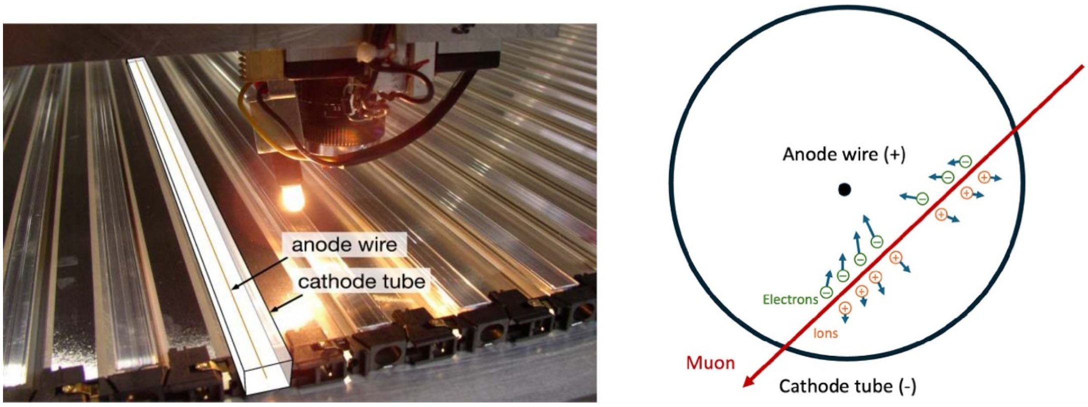

Figure 5. Left: A view of the drift tubes in the CMS detector. The overlaid graphics depict the anode wire in the centre of the tube and the cathode tube around (Reproduced with permission from [Drift tubes in the CMS detector]) (https://cds.cern.ch/record/1431514/files/oreach-2003-003.jpg). Right: A cross-section of a drift tube. This shows the movement of electrons and positive ions, when a muon travels through the drift tube and ionises the inert gas.

using ionisation. For example, the drift tubes in the Compact Muon Solenoid (CMS) detector are metal tubes filled with inert gas, and with a thin wire in the centre, as shown in figure 5 (left). A high voltage is applied between the two parts of the drift tube. As muons travel through the drift tubes, they ionise the gas. The freed electrons then move towards the anode wire, creating an electric signal, as shown in figure 5 (right). Drift tubes are structured in layers to enable the reconstruction of the muon track in three dimensions (Bayatian *et al* 2007).

3.1.8. Curriculum links and classroom resources.

When learning about new particles in the classroom, muons can be introduced as the heavy cousin of electrons. Muons are produced both in particle accelerators and at the top of the Earth's atmosphere when high-energy cosmic particles collide with air molecules. These collisions result in showers of secondary particles, including muons. In fact, approximately 600 muons cross our body every minute (www.energy.gov/science/doe-explainsmuons). While most other particles either quickly transform into new particles or lose energy when passing through the atmosphere, muons can reach the ground and can be detected. Detection of muons at ground level is evidence of the special theory of relativity, as muons only reach the ground due to time dilation (Dunne *et al* 1998). The relativistic time dilation for muons can be demonstrated using two Geiger–Müller tubes, a simple electronic circuit and a Raspberry Pi (Singh and Hedgeland 2015).

Muons can easily be detected using simple DIY cloud chambers. These use dry ice and isopropanol to reveal the tracks of particles, allowing students to see particle tracks being created in real-time (https://doi.org/10.5281/zenodo.10955303).

3.2. Combining the information

By combining the information provided by the sub-detectors described above, physicists can reconstruct the particles produced in a single collision.

Figure 6 demonstrates the interaction of various particles as they travel through a slice of the CMS and ATLAS detectors. Depending on the interaction (or lack thereof) of the particle in the different sub-detectors, we can identify its nature. For example, as a photon is electrically neutral, it will go through the Silicon Tracker (inner tracking system) without interacting (hence, a dashed line), but will deposit all its energy (and therefore stop) in the Electromagnetic Calorimeter, in the form of a particle cascade.

3.2.1. General curriculum links and classroom resources.

During the drawing activity Connect the Dots! learners from 10 years old can learn

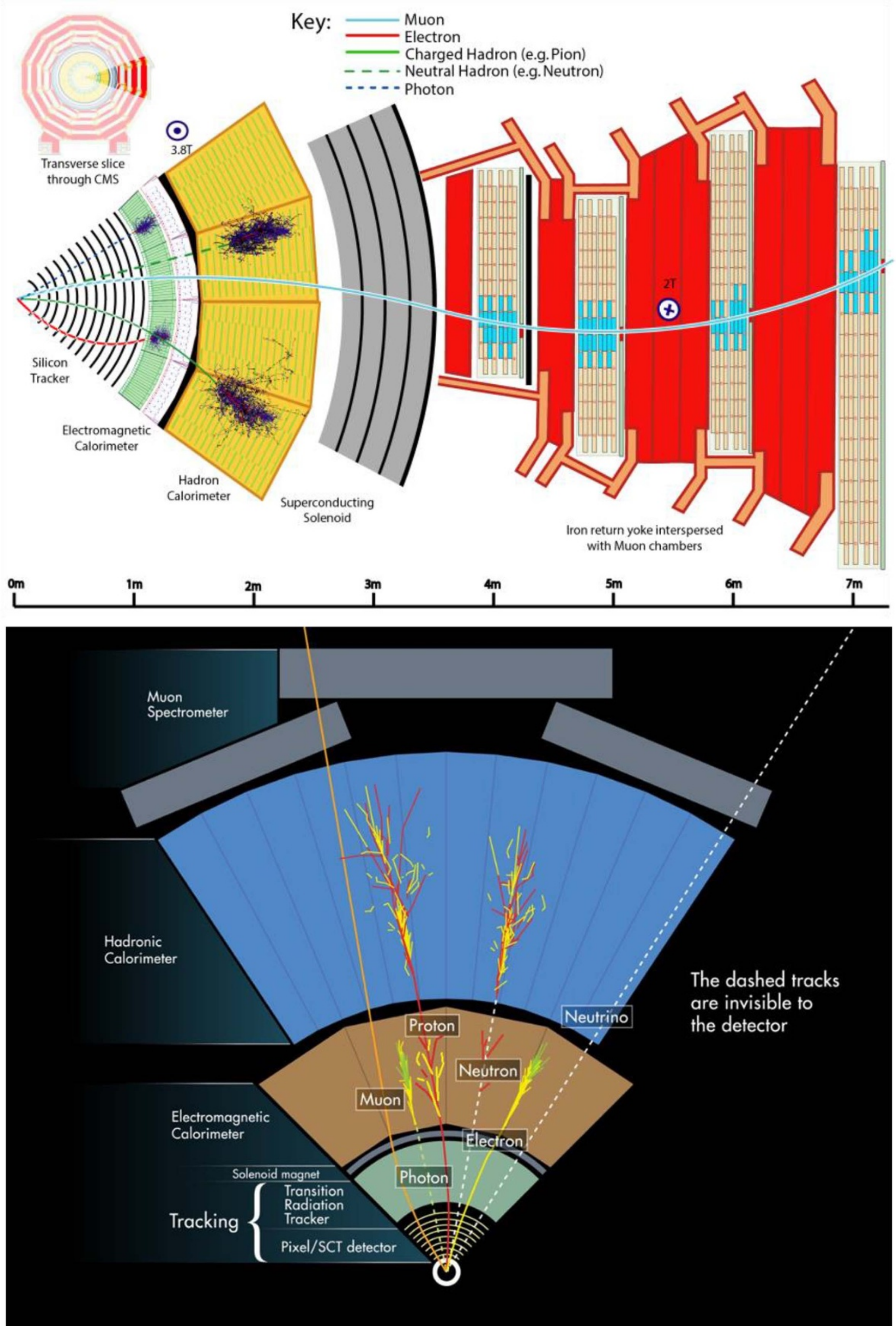

Figure 6. Particle interactions in a transverse slice of the CMS detector (top) and the ATLAS detector (bottom), from the beam interaction region to the muon detector. (Reproduced from [Particle interactions in a transverse slice of the CMS detector]. CC BY 4.0.) (https://cds.cern.ch/record/2270046/plots). (Reproduced with permission from [ATLAS detector]) (https://cds.cern.ch/record/2770815). An interactive version of the CMS image and an animated version of the ATLAS image are available online (https://cmsslice.web.cern.ch/; https://videos.cern.ch/record/2770812).

about the basic principles of tracking with multiple layers of detector material and identify different types of particles (https://connectdots.web.cern.ch/). To discuss the difference between observation and inference, students aged 12–16 can analyse animal tracks in an activity developed by the Perimeter Institute (https://resources.perimeterinstitute.ca/products/the-process-of-science). In the more advanced activity Finding the Top Quark students aged 16–19 can develop an advanced understanding of momentum and energy conservation while analysing different tracks produced in particle collisions (https://resources.perimeterinstitute.ca/products/finding-the-top-quark).

4. Conclusions

Particle detectors are essential in helping us to understand the particles that make up our universe, and therefore its origin, composition and evolution. This paper describes the main subdetector layers involved in particle detection and identification, namely the magnet system(s), the inner tracking system, the calorimeters, and the muon system. In doing so, it reveals the complexity involved in studying particle collisions.

Although particle detectors are extremely complex, their fundamental principles rely on concepts that are already taught in upper secondary school physics lessons (16–18 year olds), offering the perfect opportunity to bring modern physics into the classroom. By including curriculum links and resources, this paper provides a clear way for teachers to introduce these ideas, and by connecting these concepts to practical applications, it allows teachers to bridge the gap between theoretical physics and everyday life. Integrating education and research, in this way, remains vital for fostering curiosity and knowledge in the field, and inspiring the next generation of physicists.

Data availability statement

No new data were created or analysed in this study.

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