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Study groups

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SG1 Medical applications of particle physics: Global Teaching Perspectives

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Curriculum & classroom connections

Particle physics has increasingly become more prevalent in high school curricula all over the world. The authors consider that it should be mandatory for all high school students to have at least basic exposure to particle physics topics, specifically applications to medicine, which play a crucial role in today's society. This exposure is important since it could be a motivating factor for students to pursue careers in related fields.

Looking at the Physics curricula of the five different countries of origin of the authors, we observe that medical applications of particle physics is present in all curricula; however to different extents. For the English subsystem of education in Cameroon, for the Cambridge system in Romania, for the Ontario provincial curriculum in Canada and for the Latvian system, the connection between radioactivity and medicine is found in the curricula as follows: effects of radioactivity in living organisms, diagnostic tools (X-rays, CAT, MRI) and their operating principles with the advantages and disadvantages of these three methods. In addition, Ontario also includes PET in its curriculum, while Greece briefly mentions the basic concepts associated with such technologies. None of the curricula include the most recent advances in the field such as hadron therapy and carbon ions. Economic and political aspects of the medical applications are also neglected in the curricula. We propose more frequent reviews of the curricula in the countries considered in this study, so that updated content is included and students gain more awareness of scientific activity in the field of medical applications of particle physics. We also feel that research facilities could have a stronger focus on sharing recent findings with the teaching community, for instance through websites, workshops and/or the development of teaching materials.

For the English subsystem of education in Cameroon, medical applications of particle physics were introduced into the curriculum in 2014, including X-rays, MRI and CAT.

For the Cambridge curriculum in Romania, Particle Physics topics are first taught in high school at the end of year 11, with presentation of the basics of radioactivity. It is worth mentioning that all students are required to take this Science course, while in year 12 and 13 they can choose Physics, Chemistry or Biology courses depending on their future plans for university. The curriculum for year 12 starts to get into depth of Particle Physics knowledge, such as the description of atoms, nuclei and radiation, with topics from Fundamental particles introduced only in 2016 in the curriculum. For year 13, the curriculum contains mass defect and nuclear binding energy, radioactive decay, an understanding of the production of X-rays with examples of applications, including X-ray imaging, the purpose of CT scanning with its principles and the development of the image of an 8-voxel cube and nuclear magnetic resonance imaging.

For the Ontario provincial curriculum, grade 12 Physics was officially revised in 2008, with the introduction of PET scan in addition to X-rays, MRI and CAT. The Latvian system is currently in the process of being updated, so changes in particle physics topics are expected.

Key ideas

For medical applications of particle physics to have meaningful instruction in high schools around the world, it is imperative for high school students to know why particle physics matters. Firstly, it has revolutionized the way we look at the universe. Along the way, it has made significant impacts on other fields of science including medicine. It has developed the technology needed to very accurately track particles as they collide and transform into hundreds of other particles. This type of tracking is now used in CT, MRI and PET scans that allow doctors to peer inside the human body to see what is wrong. Once a disease is diagnosed, it is up to the doctors to determine the best treatment. Prescription medications are often the first choice. Many medications are developed at particle accelerators called synchrotrons, which evolved out of particle physics research. These accelerator-based machines produce exceptionally intense beams of X-rays that can determine the precise structure of viruses and mutations that cause diseases and screen potential drug candidates to find the ones that will be most effective. Drugs developed in this way include Kaletra, one of the most prescribed AIDS medications, and Tamiflu, an antiviral treatment that slows the spread of influenza.

Other treatment options have been advanced through deeper understanding of subatomic particle behavior, including accelerator-based therapy. Each year tens of millions of patients receive X-ray, proton, and ion therapy to treat cancer at more than 10,000 hospitals and facilities around the world.

The authors agreed that the most important aspects of the topic of medical applications of particle physics to be brought to the classroom at the high school level include the basic physics concepts associated with the technologies, their medical purposes and usefulness (diagnostic, treatment, etc), potential side effects, basic details regarding manufacturing and operation of equipment, the costs involved for the patients and the health care providers and general challenges in the implementation and distribution of technology. Additionally, exploration of career paths in the field and the main functioning centers around the world could be discussed in the classroom. Time permitting, a brief discussion of cancer might be helpful, as most therapies are targeted to patients suffering from that condition. Finally, a brief historical and conceptual discussion of antimatter might be helpful in teaching PET.

Potential student conceptions & challenges

Student conceptions about medical applications of particle physics tend to vary. Most students seem to relate to the concept of X-ray imaging and medical imaging in general, though not the specific details of how the images are obtained, or the physics behind the construction and operation of the equipment. CAT, MRI and PET in particular are more challenging for students to relate to and learn efficiently. The more detailed and specialized the exposition of the topic, the more difficult it is for students to remain engaged. Certain terms are also unfamiliar for most students, in particular “resonance”, “axial tomography” and “positron”, among others. Students may also have difficulties in understanding which particles react with matter and how, according to their properties (mass, charge) and their effect on living organisms. They also often confuse the names of the particles. Another challenge for students is to understand which physical properties are being applied to diagnose and cure illnesses.

Elements of medical applications of particle physics that might obstruct a successful introduction in the classroom are, besides technical terms, the details of operation of the related equipment and details regarding imaging formation. It has been observed by one of the authors under the Ontario curriculum that basic explanation of key terms, basic explanation of the history of development of the technologies and basic explanation of the physical principles involved tend to have a more positive effect in the classroom.

Helpful material and resources

The authors have observed in their practice that the textbooks generally utilized at the high school level are limited in content and generally uninspiring. CERN’s website is helpful in filling in content gaps and inspirational gaps in the high school texts commonly used. It also provides updated information on present and future expectations regarding the topic of medical applications that might be of interest to both teachers and students to further their understanding of the subject. It is also understood that each separate medical application has its own sources of educational material, both online and in texts; however it is generally found that a comprehensive and updated guide and/or summary review of all applications, as well as helpful educational activities and labs, are currently lacking in the literature at the high school level.

There are many resources available online which teachers can use as inspiration. Every good lesson should have at least 3 types of activity in it (theory, practical or computer simulation and a video with the latest trends and discoveries in the field). For the countries in this study, the practical part tends to be impossible to do, due to the lack of equipment.

A good source of simulations is the “Simulations site of the University of Colorado at Boulder” (https://phet.colorado.edu/en/simulations/category/physics/quantum-phenomena), where some basic concepts of particle physics are explained. Of course, these simulations are to be used in class at the basic level, since as we get deeper into the topics we find that they have limitations. At the same time, lots of animations and videos can be found on YouTube (www.youtube.com) explaining medical applications of particle physics. The “Accelerated Education Program” (AEP) channels video (https://www.youtube.com/watch?v=t8Q23XhqAhc), as another example, explains how radiation therapy works.

One more excellent source of particle physics teaching resources is the TES website, addressed to a lot of curricula and to a lot of subjects or age groups (https://www.tes.com/resources). In addition, the “TeachEngineering” website (https://www.teachengineering.org) is a digital library where various teaching resources can be found regarding engineering; see for instance the lesson “Magnetic Resonance Imaging”.

Useful materials also can be found on the SIEMENS website. SIEMENS has part of their website dedicated to education (http://www.siemens.co.uk/education/en/), where also lesson plans about how MRI scanners produce images can be found (Lesson “A Peep Inside”).
The following additional links might also be helpful:
http://filestore.aqa.org.uk/subjects/AQA-2450-W-TRB-OGMP.PDF, http://filestore.aqa.org.uk/resources/physics/AQA-7407-7408-TG-MP.PDF, https://resources.collins.co.uk/Wesbite%20images/AQA/Physics/sb2module/9780007597642_Medical%20physics.pdf, https://www.stem.org.uk/resources/collection/2958/medical-physics

Best practice example

Regarding their individual practices and personal suggestions for improved teaching of the topic considered, the authors agreed on the following:
Simulations and videos related to each medical application are helpful in the classroom, as well as projects on which students work in groups, search for information on the internet and present their findings. Questions and answers also facilitate the learning process.
Field trips could be organized with students to university particle physics labs or research institutes. Students who choose to take these more advanced Physics classes in high school have usually already decided to pursue careers either in engineering or medicine, so a really good source of information and potential visit site could be oncological hospitals, which can be found in most countries and city centers. In such a manner, the interest in the subject from the student’s perspective increases exponentially, since they realize the application to their career.
One of the authors recommends beginning a new unit of study by clarifying the purpose and learning goals with the students and providing explicit criteria on how they can be successful. Then, the teacher should occasionally step offstage in order to facilitate entire class discussion, allowing students to learn from each other. Next, individual feedback to the students is encouraged, so that the learning process, as well as material and instruction can be adjusted accordingly.
Interdisciplinary lessons including input from biology, chemistry and computer science teachers are also considered to be very productive.
In conclusion, a potential instructional strategy could be proposed based on our experience at CERN: starting with historical considerations, the teacher could then expound the basic physical concepts of radiation, proceeding to a general discussion of imaging, diagnostics, treatment and side effects. Then, operational and safety aspects of equipment, economic considerations and finally an outlook into future developments can be mentioned. The details in each section of exploration can be added according to grade level and general time allocated to the topic, as well as varied official curriculum expectations. Finally, all the authors agreed that a professional or expert in the area could be invited to the classroom to share their knowledge and experience with the students directly, as they could better answers student’s questions and be a source of inspiration for the pursuit of careers in related fields.

SG2 Particle accelerators

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Curriculum & classroom connections

All the group members teach high school's student around 16-18 years old. In all the curriculums the main highlights are Mechanic, Electromagnetism and Modern Physics. The topic of particle accelerators appears to be in several curriculums but with little reference.
Although, all the group members agreed that most of the basic knowledge that student needs to understand the physics of particle accelerators is in the curriculums.

For example, in Mechanics we teach about motion equations ($x = x_0 + v_0 t + \frac{1}{2}at^2 \qquad v = v_0 + at$) and circular motion equations ($a_R = \frac{v^2}{R} \quad \Sigma F = m\frac{v^2}{R} \quad \omega = \frac{\Delta\theta}{\Delta t} \quad \omega = 2\pi f = \frac{2\pi}{T}$) and kinetic energy ($E_k = \frac{1}{2}mv^2$) and momentum ($\vec{p} = m\vec{v}$) . In electromagnetism, in the introduction part, we teach about the atom structure and ionization. Furthermore, we teach about electric field and electric force ($\vec{E} = \frac{\vec{F}}{q}$) as well as magnetic field and force ($\vec{F} = q\vec{v} \times \vec{B}$).
When we teach magnetism we speak about the cyclotron structure and action principle. Additionally in the Modern Physics part we teach about the Theory of Relativity and the equivalent between mass and energy ($\Delta E = \Delta mc^2$).
With all this knowledge we believe that the student will have a solid foundation to learn about particle accelerator.

Key ideas

At first the students should learn:
The need of accelerating particles: why do we need to accelerate particles and ions?
In this topic we need to use some basic concepts from electromagnetism, one of the four basic interactions of nature:

- Electric field: used for accelerating charged particles, the students are used to consider constant fields in plates, so we need to introduce electric fields which change polarity at the resonance cavities.
- Magnetic field: used for curving paths, but not for accelerating purposes.
- Motion of charged particles in magnetic fields: introducing cyclotron frequency and radius.
- Electrical current: they must be able to understand that bunches in the beam are electrical current too.

On the other hand, they need some knowledge from kinematics and dynamics:

- Acceleration: they are used to motion under constant acceleration.
- Circular motion: understanding the effect of centripetal force.

They need some knowledge about:

- Atom structure.
- Ionization.

Relating to modern physics, and especially to relativity:
- Maximum reachable speed, even when we use more and more energy, the particles will nor reach the speed of light.
- Energy: when the particle is travelling at a speed which is near to the speed of light, a big amount of energy will only produce a little increase in its speed, but the particle will carry more energy.

They need to understand too:
- Particle injection: particles cannot be directly injected at a big accelerator, they must be sequentially accelerated by different devices (LINAC, PS and SPS at the LHC).

And for this, they must understand:
- Different kinds of accelerators: there are linear or circular accelerators.

Potential student conceptions & challenges

Following topics will illustrate a successful introduction
1. How mass and energy can be converted into each other.
2. Although atom is neutral then from where we get a charge particle to accelerate?
3. How does a charged particle get accelerated?
4. Can a neutral particle be accelerated?
5. Construction of a cyclotron. It is difficult for the students to understand only with the help of diagram.
6. In a cyclotron, why does a particle move in circle but not in a straight line?
7. Which force bends the trajectory of charged particle in the cyclotron?
8. Understanding of direction of magnetic force on charged particle in magnetic field.
9. What is the meaning of cyclotron frequency?
10. Results of theory of special relativity.

Helpful material and resources

Presentations:

rudi.home.cern.ch/rudi/.../Kapitel1-Introduction.pptx

https://www.scientificofoligno.it/documenti/Area_Scientifica/as_2015_2016/PHYSICS%20CLIL%20PROJECT.pdf (Activity CLIL)

http://www.aps.org/units/dpb/upload/accel_beams_2013.pdf

http://uspas.fnal.gov/materials/09UNM/Unit_1_Lecture_1_Motivation.pdf

- Material on the websites:

for example the CERN Website https://home.cern/about/accelerators and http://www.accelerators-for-society.org/

- Videos on YouTube :
  https://www.youtube.com/watch?v=328pw5Taeg0
  https://www.youtube.com/watch?v=328pw5Taeg0
  https://www.youtube.com/watch?v=esnqn_vutH4
- Laboratory activity:

http://www.scienceinschool.org/2014/issue30/accelerator

- Exercises:
  https://particlephysicsassessments.wikispaces.com/Particle+Detectors+and+Accelerators

  PARTICLE ACCELERATORS AND DETECTORS-short Answers Latest.ppt

- Masterclasses in particle physics (https://home.cern/students-educators/updates/2014/03/masterclasses-particle-physics)

Best practice example

The aspects we consider important for the students to understand:

1. Why do we need to accelerate the particles?

A tool to investigate the structure of the atomic nucleus and particles. If we observe smaller objects, we need them "shine" waves of wavelength less than or comparable to the size of the object.
For example :
The interaction between nucleons is limited to a range less than 1.10^{-15} m. A particle which is responsible for the interaction of two nucleons should have a mass in the order of 200 MeV !!!

2. You can only accelerate charged particles and ions !
   Electric force F= E.Q only acts on charged particles a magnetic force acting on charged particles by Lorenz's force that curves the trajectory of the particle.
3. The basic principles of the accelerators
   Repeat : Electric force, Lorentz force, Flemings rule for the orientation of the vector of magnetic induction, magnetic force and power, a circular motion, relativity- change in weight, the conversion of mass into energy, units $1eV=1,602.10^{-19}$ J, $1TeV=1,602.10^{-7}$ J. Accelerators are safe because TeV is a large unit in the micro-world but small in the macro world.
4. How an accelerator works?
   - two main groups : linear accelerators, circular accelerators.
   - The main components of an accelerator :
     a) Radiofrequency (RF) cavities and electric fields – these provide acceleration to a beam of particles. RF cavities are located intermittently along the beam pipe. Each time a beam passes the electric field in an RF cavity, some of the energy from the radio wave is transferred to the particles.
     b) Magnets – various types of magnets are used to serve different functions. Dipole magnets are usually used to bend the path of a beam of particles and quadrupole magnets are used to focus a beam.
     c) Vacuum chamber – this is a metal pipe (also known as the beam pipe) inside which a beam of particles travels. It is kept at an ultrahigh vacuum to minimize the amount of gas present to avoid collisions between gas molecules and the particles in the beam.
5. Use of accelerators and new technology in practice, for example in medicine – radiotherapy, in art history: particle beams are used for non-destructive analysis of works of art and ancient relics and in the industry in order to produce smaller and smaller devices.
6. For a better understanding of the topic, the students need to indicate examples of everyday life, enjoy the videos, animations, applets, and also solve (calculating) simple tasks to understand the relationships and patterns between variables and parameters. It is necessary to use activating methods and forms of teaching (eg' dialogue, discussion, problem solving, group work, searching for information on the Internet and in books, papers).

SG3 Particle Detectors in the High School Classroom

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Curriculum & classroom connections

Particle physics and concepts relevant to particle detectors are typically first introduced in schools around 16-18 years old. This report is written with students of this age in mind and does not address topics beyond the scope of fundamental particle detector principles; specific detector engineering and data analysis have not been included. Most physics curricula require the knowledge of different types of sub-atomic particle and their properties. Within this report, knowledge of particle properties is considered a prerequisite, though we have proposed an activity in which these could be introduced to students. Conversely, detailed understanding of different types of detectors is not typically required by curricula, but they serve as a valuable tool for understanding the principle of indirect measurement.

One of the most universal school physics topics is electromagnetism. When students are comfortable with the interaction between a magnetic field and moving electric charge or current, the use of magnetic fields to influence the trajectory of a charged particle in detectors may be introduced and is relatively straightforward. For more advanced students, calculations of this Lorentz force may be performed.

Students are likely to already be familiar with ammeters and voltmeters. While they may not have considered the mechanisms behind these instruments, parallels can clearly be drawn with particle detectors: an ammeter provides some measure of the movement of charged particles, and a voltmeter provides an indication of their energy.

An outline of additional classroom connections is illustrated in Figure 1 below.

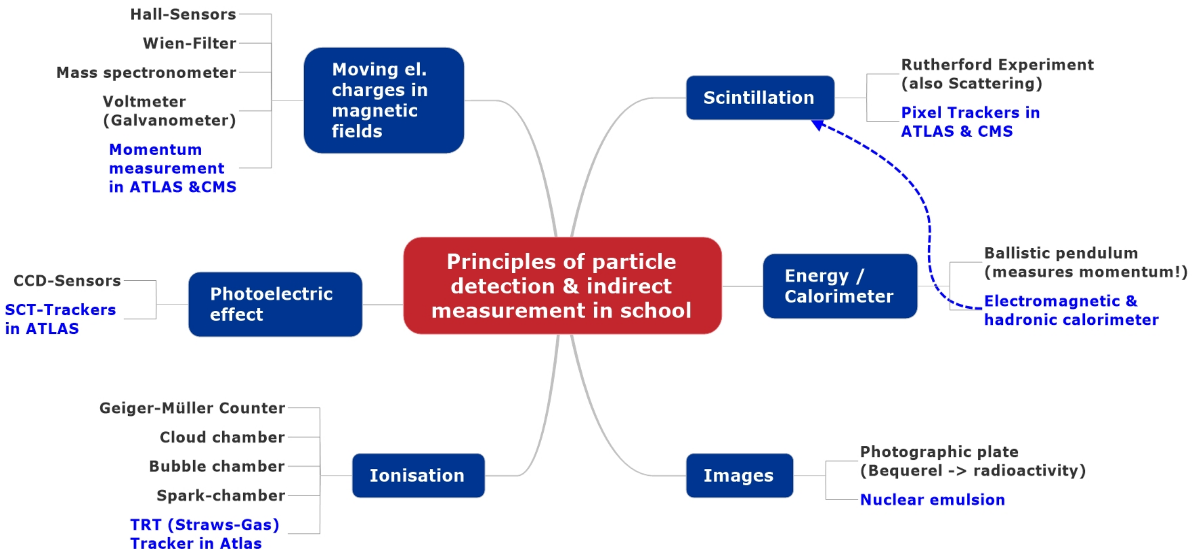

Figure 1. Principles of particle detection connections to standard high school curricula

Key ideas

The word ¨detect¨ means ¨to discover or identify the presence or existence of something¨. This is often conceptualized within the context of the human senses. However, when considering particle detectors, particles are identified by examining their interactions with each other, materials and within fields, as dictated by their properties.
The three key principles of particle detection can be summarized as: (i) particles have certain observable properties, (ii) making indirect measurements, and (iii) the principle of detecting and identifying particles by designing systems that utilize their interactions with various media (ionization, use of magnetic fields). From this a particle's properties can be inferred, subsequently enabling the identification of the particle.

Potential student conceptions & challenges

Phrases which cause difficulty, challenging aspects of the topic:

- Particle physics, unlike Newtonian physics, has the complication that observation of particles changing their behaviour. It may help students to give an analogy, but relatable analogies typically rely on classical physics. One potential analogy is recording the behaviour of nocturnal animals; the act of using flash photography causes the animals' behaviour to change.
- A second consideration is the energy loss during detection; again this could be addressed with an analogy, for example calculating wind speed with an anemometer must take the friction of the device into account.
- Particular care must be taken when describing particles and phenomena using analogies: stating that "Positively charged particles repel one another, like magnets" is self-referential; we are describing the electromagnetic force using the electromagnetic force. Consequently, any misconceptions a student may have with the analogy are compounded rather than resolved.
- To infer the electric charge of a particle, the interaction between charged particles and a magnetic field must be understood. This is typically covered after the principles of circular motion have been studied.
- Scientific methodology, such as taking large numbers of readings to reduce the impact of "noise" is of particular importance with electric detectors, since the charges involved are so small.
- 3D thinking is a challenge both for students (constructing their own understanding) and for teachers (representing these visually).

Helpful material and resources

Pictures and posters

- Schematic picture of ATLAS detector: https://mediastream.cern.ch/MediaArchive/Photo/Public/2008/0803012/0803012_01/0803012_01-A4-at-144-dpi.jpg
- Poster of ATLAS detector: http://cds.cern.ch/record/2155753/files/CERN-Brochure-2016-001-Eng.pdf
- Schematic poster of CMS detector: https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=4263&filename=CMS_English-2013-03-22.pdf&version=1

Lectures

- The Physics of Particle Detectors: http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L1_Introduction_HEPdetectors.pdf
- Mar Capeans Lecture & Slides on Particle Detectors during HST2015: https://indico.cern.ch/event/355973/contributions/1766251/

Videos

- CERN Media and Press Relations animations and videos: http://press.web.cern.ch/videos-animations

Best practice examples

- Indirect measurement activity 1: http://www.pas.rochester.edu/~pavone/particle-www/teachers/demonstrations/Marbles.html
- Indirect measurement activity 2 (Activity Four): http://www.cpepphysics.org/Class_act_e.html
- Interactive animation of footprints from elementary particles in the ATLAS detector: http://atlas.physicsmasterclasses.org/en/zpath_playwithatlas.htm
- Chart: "What particle are you?": http://blogs.discovermagazine.com/cosmicvariance/files/2012/04/WhatParticle3.png
- How to build a Cloud Chamber: https://youtu.be/xky3f1aSkB8

Helpful material for students

- Posters of the Standard Model (in different languages):
    - http://ippog.org/resources/2015/multilingual-poster-about-elementary-constituents-matter
    - http://scienceblogs.com/startswithabang/files/2013/08/chart_2006_4.jpg
    - http://www.cpepphysics.org/
- LHC detector websites:
    - https://atlas.cern/
    - https://cms.cern/detector
    - http://lhcb-public.web.cern.ch/lhcb-public/en/Detector/Detector-en.html
    - http://aliceinfo.cern.ch/Public/en/Chapter2/Page3-subdetectors-en.html
- Videos:
    - An introduction to the CMS Experiment at CERN: https://www.youtube.com/watch?v=S99d9BQmGB0
    - ATLAS - Episode 2 -The Particles Strike Back (Part 1 & 2): https://www.youtube.com/watch?v=iYRQpcJVQx8&t=204s https://www.youtube.com/watch?v=DUkzyDbMQ3E

Best practice example

Our suggestion for a lesson introducing particle detectors comprises three parts, scaffolded to guide students through the three key ideas discussed above.

The popular game “Guess who?” can be adapted to examine the differences between particles rather than people. This can be used as a starter activity to revise particle properties, before leading into an examination of the questions that were being asked (for example, “Are you a positively charged particle?”). Since we cannot “ask” questions of sub-atomic particles, we must instead use detectors to divine the answers.

To address the fundamental principle of indirect measurement, two versions of an activity are proposed. In the first, students roll ordinary marbles towards an irregularly shaped object hidden under a sheet of cardboard or wood. By tracing the incident and post-collision paths, one can deduce the shape of the unknown object. A discussion of detector resolution can be made if students are allowed to repeat the experiment using smaller marbles. The second variation of this activity involves the addition of magnetic marbles and iron filings to more accurately track their paths as well as to illustrate the challenge in detecting neutral particles. Here, a sheet of cardboard is elevated slightly above the floor to allow the marbles to roll underneath and a thin layer of iron filings is added to the top of the cardboard. A collection of magnetic marbles are placed at random intervals beneath the cardboard, allowing periodic collisions between the primary marble (ordinary or magnetic) and the magnetic marbles. In this way, we are able to model secondary measurements made by particle decay.

The cloud chambers activity delivered by the S^{J}Cool Lab workshop would make an excellent consolidation activity for students. The properties of the electron, muon and alpha particles would have been introduced in “Guess who?” which will means students will have a better appreciation of what they will be looking at in the cloud chamber. After setting up the chamber, images of what particle tracks to look for can be introduced to the students and a discussion can take place on why different tracks look the way they do and how this can be used to infer particle properties and types. Additionally this activity can link to the indirect measurement concept introduced by the ‘marble’ activity. This can be achieved through an explanation of how charged particles through ionization causes the condensation trails similar to the magnetic marbles causing an iron filings trail. Following further observations of the cloud chamber a discussion could take place on background radiation as well, how radiation is all around us both from cosmic rays and radon gas and how this background radiation would need to be accounted for when attempting to discover new particles.

SG4 Computing – Introducing high energy physics computing to the secondary classroom

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The development of information and communication technologies in the past few decades has been felt in all areas of human activity. Education is no exception, where there are with many possibilities to develop the understanding of such technologies. Using different available software packages online, students should be encouraged to become familiar with computing through a variety of forms and modes. With the help of computers and appropriate simulations, some of the more difficult concepts of physics can be explained and understood in a more simple and easier way.

Wherever possible, real experiments should be carried out but there are areas where it is not possible to display and observe a particular physical phenomenon in school conditions. In this case, computers and simulations are great help for explaining and visualizing physical phenomena. Particle physics is one of such areas.

The simulations and computer programs that we will discuss will offer great opportunities. However, everything depends on the teacher. The teacher should devise the use of modern teaching tools and help students to use them in the right way. In everyday work, a student should be an active participant, and not just an observer for what the teacher is doing.

Good teacher + black board = good teacher

Bad teacher + computer = bad teacher

We will be looking at how the complex computing concepts that are used at the LHC may be simplified and fit into the current school and college curricula.

Curriculum & classroom connections

Scientific Computing as a subject is not often studied as a separate entity within schools and colleges, but is one that is growing in popularity as we become more of aware of the need for computing in society. Computing specifically in the context of particle physics crops up even more rarely than general computing, but there are some links to the current curricula around the world and plenty of potential areas where computing can be integrated, including data collection, analysis and using computing to discuss international collaboration.

We initially identified the existing learning broadly, with a focus on particle physics, across the college and high school curricula and areas of potential learning to incorporate the idea of computing. We found that on the whole, particle physics and high energy physics is not met until later on in students' educational careers, generally between 16-19 years old. Basic nuclear physics is taught previous to that, but not in much detail. With regards to computing, generally this is not currently taught explicitly and if it is, then it is an optional subject that is chosen by students who know that they want to study computing further.

Although there do not appear to be many current direct links between computing and existing syllabi, we identified many areas that we could perhaps incorporate what we have learnt into our lessons and courses. The following are a list of potential areas of learning where CERN computing could be brought into the classroom:

- Dataloggers in any experiment where they can automate data collection to model what happens at the LHC and to discuss the need for automation of collection data. This can be used to bring in the idea of the scale of the volume of data collected at CERN and therefore the need for automation.
- Data analysis in any practical experiment that they might carry out where they will have measured variables and learning to manipulate that data in a way that will lead them to a valid conclusion.
- Simulations for particle interactions when introducing fundamental particles and the standard model as part of a nuclear physics or introduction to particle physics topic.
- Mathematical modelling and statistical distributions whenever students are collecting data or discussing experiments where a large amount of data is necessary for a data to be deemed reliable e.g. gas laws and nuclear reactions.
- Databases when carrying out experiments where a large amount of data needs to be collected, stored and then retrieved by students at a later date.

Key ideas

Computing is an emerging field and comprises multiple disciplines within the field of Science and Engineering. At CERN and the LHC, computing is necessary after events have been detected by the hardware of the four main detectors before it is sent for analysis at CERN and across the globe. Although that may be the most obvious application of computing, there are other areas that computing may be used across CERN:

- Design of colliders and other facilities at CERN, e.g. in the architecture. For example, the use the CAD programme Autodesk to prepare models of the colliders, machines and buildings to be used at CERN.
- Simulation of high energy physics to design the experiments and provide predictions that will be used to aid the discovery of new particles. Computing may also be used in visualising events, converting the signals that are received by the detectors to form visible representations of the events.
- Programming of automated safety controls to protect human life and preservation of the machinery, and maintenance of collider.
- Extracting, storing and analysing all data obtained. Computers are necessary to gather signals from detectors and in filtering useful data that will then be analysed. The data that is gathered needs to be distributed across the grid network to be analysed.
- Collaboration and communication across a very large international network, which requires a robust and comprehensive infrastructure to support the needs of all users across the system. A fast network is also needed to allow communication to take place in real time.

Potential student conceptions & challenges

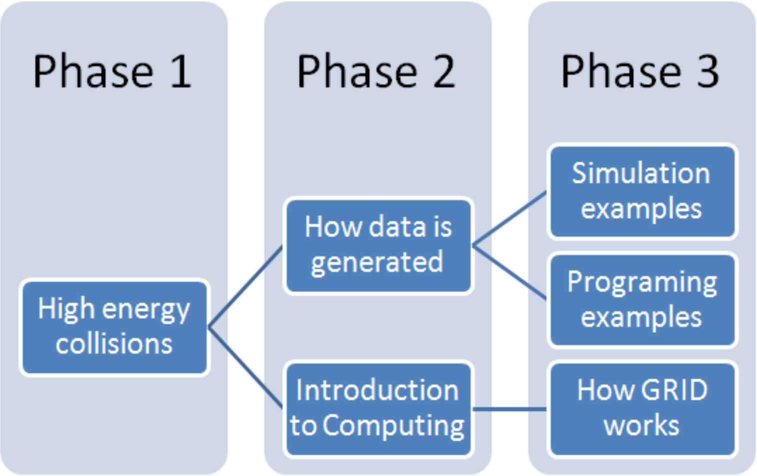
As computing is a subject that may be unfamiliar to many of our students, they are bound to have some misconceptions that may present many challenges to their understanding. These may range from simple questions to the wider, more abstract concepts involved.

- Students may come in with preconception that computing is a difficult, which may be due, in part, to a lack of understanding of what computing actually involves.
- Without a good basis in statistical evaluation techniques, students may have trouble perceiving the scale, complexity and statistical nature of collisions. They may find it difficult to appreciate that there are many data points that are collected, as they may only be used to collecting singular data.
- During analysis, calculations and simulations, there are many assumptions that are made, which students may not always appreciate or understand the need for.
- Students may find it difficult to comprehend that 99.99% of the data is filtered at the first step of the detector. They may question what happens to that data and what could be hidden within that data, specifically at CERN, but also understanding in general how much of the data that is obtained is useful.
- Perhaps the most fundamental misconception or source of confusion might actually be the question "What is data?". Students may be more familiar with their laboratory experiments where they carry out a method and obtain data points and measure variables, and may not be able to translate that to the idea that data in computing will be a series of millions of 1s and 0s that are stored.
- Students may also then wonder why we cannot use one large supercomputer to compute the data, and ask why we might use a grid instead.

Having pre-empted some of these misconceptions, teachers can then work to address them and help students gain a better understanding before their misconceptions become too far embedded as to impede their learning.

- (Over 50% of LHC computing is associated with simulations). Introduction to the concept of simulation and modelling at high school or secondary level either with Hypatia or Geant. GEANT has an excellent set of examples that can help make their conceptual visualization of the processes involved at the LHC better.
- At this level, if they are familiar with programming, ROOT can be an interactive way of letting them understand to the extent they gain an interest in HEP.
- GRID computing is the core of future HEP. In most of text books of computers an initial knowledge of networking is in their curricula. This level can be enhanced by inclusion of a GRID computing topic at primary level and presented in an interactive way. The LHC can be used as example of GRID, Tiers, Wigner Center linkage and job distribution to illustrate this concept.

It is indeed not expected that the young students will understand the modelling and simulation of actual practical events or solve higher order differential equations at this age but an idea of parallel processing and its linkage with HEP can be understood. Communication can be done as per the time allocation in the syllabi in three phases viz;



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Helpful material and resources

There are many different software packages that are available to introduce computing and for students to use to analyse real data. Below is a selection of such software that can be used for the various aspects of computing.

- To aid in the understanding of the infrastructure of particle accelerators in general and using models to build machinery, one can use http://www.acceleratar.uk/. This can help students to grasp the idea that computer programs can help us to model large scale projects and to help us to design facilities without having to build anything. It can also be used to teach more generally about the structure of a particle accelerator. An alternative program to model large scale objects would be Autodesk, which is available for free to students and educators.
- To help students visualise particle collisions, the Virtual atom smasher (CERN) test4theory.cern.ch is available, along with https://phet.colorado.edu/en/simulations/category/physics/quantum-phenomena from Phet Interactive Simulations – University of Colorago. Students can also program their own simulations using the simple block programming tool Scratch scratch.mit.edu. Alternatively, they can learn to use CERN's own packages, https://root.cern.ch/ and http://geant4.cern.ch/.
- CERN also provides free access to the user interface directly from the control room to allow students to see the data that is being collected from the LHC in real time through their Vistar website. https://op-webtools.web.cern.ch/Vistar/Vistars.php . This can help to address the concept of data collection on a large volume and time scale.
- Once students understand the idea of the volume of data that is collected, through the various simulations and visiting the CERN Vistar, they can then use Google Earth's WLCG to visualise the scale of computing power that is needed to analyse the data that is collected. http://wlcg.web.cern.ch/wlcg-google-earth-dashboard. Should they wish to research more on CERN's Grid network, they could read "The Grid" (Foster & Kesselwah, 1998).
- Students are also invited to participate in the International Masterclasses, http://physicsmasterclasses.org/. Here they learn more about the projects happening at the LHC and attend workshops to use Hypatia, http://hypatia.phys.uoa.gr/Downloads/, available for free, which allows them to analyse data in the classroom. QuarkNet is also available to allow students to view particle collisions and analyse the tracks that they see, http://quarknet.i2u2.org/.

- For more general data collection, Physics Toolbox Sensor Suite is available for portable devices that turns them into a large array of measuring devices!
- For more complex calculations, there are many other packages that allow students to solve particle equations, for example, Mathematica (Wolfram) (Paid) and SAGE (Open Source).

The list of available resources is endless, but a good place to start may be http://onlinelabs.in/physics for a variety of online simulations.

Best practice examples

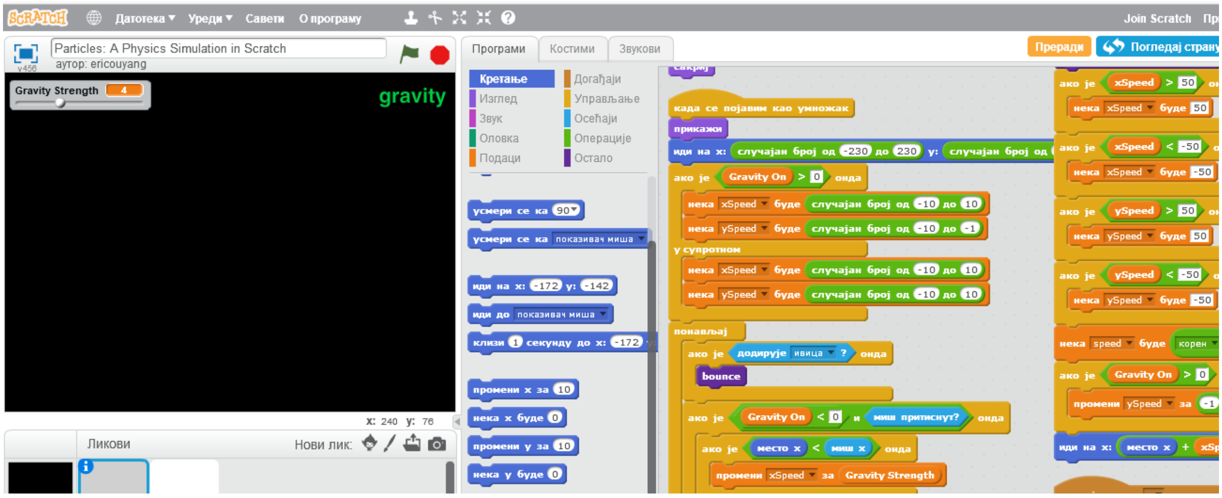
STRATEGY 1

TEACHING STUDENTS HOW THE HIGGS WAS DISCOVERED WITH COMPUTERS USING SCRATCH AS A PROGRAMMING TOOL

Scratch is a programming tool based in blocks. This means that code has been replaced by blocks that fit together in specific ways, making things easier for young students that approach computing for the first time.

STEP 1: UNDERSTANDING THE BASIC LAWS THAT GOVERN PARTICLE COLLISIONS

Coding something is a fantastic way to get to understand it. We take advantage of this fact to ask students to implement the conservation laws that apply in elastic two particle collisions into a small program. All the students will be given the same initial conditions and will be asked to code an animation that shows the evolution of the system.

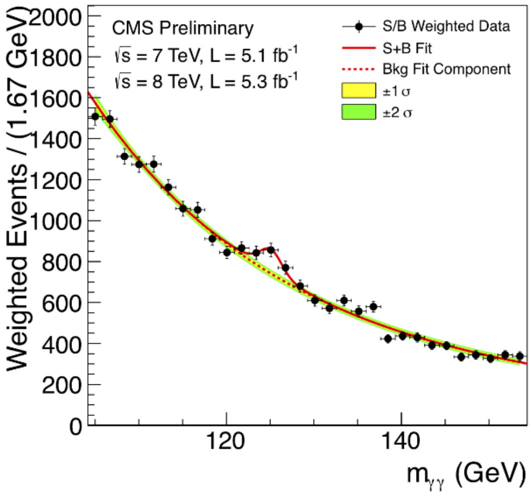


STEP 2: UNDERSTANDING THE BACKGROUND OF A PROCESS

Now creation of new particles comes into the picture. The students are organized in teams and are given a process with the same initial conditions (two protons colliding at 14TeV), but diferent outputs in terms of particle creation. At the end all the results are classified and plotted in a graph that shows the frequency of each event (in this case is trivially 1) against the mass of the output particles.

At this point the students are ready to understand that big computers are needed to simulate all the possible outputs and compute how many times each output is espected in order to plot the background for a process.

STEP 3: SEARCHING FOR NEW PARTICLES



Now this plot should be clear for the students in terms of the observed excess in the detectors –which are connected to a huge computing grid to store and analyse the data generated- over the calculated background. At this point the statistical significance of the excess represents another challenge for the students which might be the subject of another strategy.

STRATEGY 2

International Masterclass

The Masterclass is a project for students age 15-19. This project gives students the opportunity to discover the world of particle physics in more detail than their curriculum might allow.

Activities:

- lectures about particle physics, detectors, accelerators and all of the science behing the LHC;
- measurements on real data from particle physics experiments at CERN;
- video conference with students from other countries to discuss and combine of results.

Within this project students use the specialized educational software Hypatia to analyze the real data obtained from ATLAS and try to discover elementary particles. Hypatia is an interactive laboratory environment for particle collisions where events are recorded in proton-proton-collisions within the Atlas detector at the Large Hadron Collider.

STRATEGY 3

Dataloggers

Using dataloggers in an experiment to model data collection during particle collisions, to introduce automated and large-scale data collection and to understand the need for collaboration.

Students could carry out an experiment to measure the velocity of airtrack gliders (particles) after collision when released using repulsion of different strength magnets (differing initial energies of particles).

The need for multiple data collection can be discussed through the release of the gliders – the magnets should have the same strength across all groups, but the way in which they are released may introduce error, so multiple data points should be obtained to ensure data is true and reliable and to check that data is consistent. It can also be used to gain as a full picture of the possible collisions that could take place in this situation. The need for collaboration can also be brought in through discussion of what the true values may be and to compare data, as CMS and ALTAS did.

Once data is obtained, a plot of the background can be created and parallels can be drawn with the Higgs Boson graph.

There are many other areas of the computing cycle that can be brought in, depending on what you want to emphasize.

STRATEGY 4

It can be categorized in two parts (a) Distribution of the curricula as per the allocation of time in classroom and then

(b) Including-

(I) Collision studies

(II) Generation of data and introduction to computing

And

(III) Simulation programing and Working of GRID with examples of WLCG.

SG5 Data Analysis

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Curriculum & classroom connections

The analysis of data is a necessary process to evaluate the results of an experiment and draw conclusions. Therefore, it is a crucial part of school curriculum. The experimental method in schools is usually introduced during subject specific practicals. The measurements are then analyzed and evaluated to give a general conclusion for the investigation.

In nuclear physics data is obtained from detectors after collisions between two high energy particles. The measurements are taken by specific particle detectors. This provides information about the products of collisions, which is organized in tables and then analyzed. These tables, unlike the tables that students build after their experiments, contain a very large amount of data consisting of different values of variables of the particles measured by the detector. Once the data have been gathered, the analysis does not require mathematical tools very different from those used in well-known physics classroom experiments. However the students may not necessarily be familiar with working with large tables of data coming from a database source (in this case, this is the detector).

There are different types of analysis of data depending on the goal of the experiment. The easiest ones only require the basic statistics concepts used in simple experiments (concept of frequency and histograms). The more complex ones require the use of more sophisticated statistical tools that are probably taught in curricula containing more advanced mathematics programs (Gaussian distributions, mean and standard deviation values, line of best fit, error bars…).

The topic of particle physics and the Standard Model is not present in many of the curricula from different countries. For this reason, in order to work with data from particle collisions, some time may be needed to teach basic concepts of the Standard Model of particle physics.
In the case of the International Baccalaureate (IB) Diploma Programme (educational program for students in the last two years of high school that is offered in most international schools in the world), the topic of particle physics and the Standard Model was introduced in the Physics curriculum two years ago. Students learn the main characteristics of the elementary particles, sketch and interpret simple Feynman diagrams. The mathematics curriculum of this program (two of the three levels offered) also provides the students with the tools necessary to make the more complex analysis. Thus, students in the IB program should be ready to learn and understand the basic methodologies for the analysis of data from collisions of particles.

As these collisions deal with high energy particles (usually proton – proton collisions), the speed of the particles involved is close to the speed of light. Therefore, students also need to be familiar with the relativistic equation relating the energy and momentum of the particles. This topic is only present in some advanced physics programs and therefore it also may be necessary to introduced it in the classroom. In the case of the IB, the topic of relativity is one of four possible topics from which students chose one. So, not all the IB physics students may be familiar with this equation.

In Russia, children enter school at six, and study 11 years. Then they enter the institute. The kids study the last 2-3 years. The system of teaching is similar to the Russian university, lectures, seminars, practical work. On lecture tells about quarks, leptons, we tell about carriers of interactions photons, gluons, bosons and, of course, we mention graviton).

What follows is a chart with the mathematical and physics concepts that are needed to understand the analysis of data after the collisions.

Mathematics:	
Descriptive statistics	• Concept of event • Data tables with several columns and rows • Frequency and histograms • Normal distribution (mean and standard deviation) • Scatter plots and line of best fit • Error bars
Physics:	
Classical mechanics	• Vectors in three dimensions (magnitude, components, addition) • Conservation of linear momentum
Particle physics	• Elementary particles and the Standard Model • Simple Feynman diagrams • eV units and its multipliers (KeV, MeV, GeV,…)
Special relativity	• Relativistic equation relating energy and momentum: $E^2 = p^2c^2 + m_0^2c^4$ or $E^2 = p^2 + m_0^2$ (using eV units)

The program used in the activity proposed in the last point of this paper is implemented in python language. The students do not need to know this language as clear instructions of the steps are provided during the execution of the program. However, more advanced students are likely to learn the basics of coding in python and, consequently, will be able to make their own activities.

Key ideas

1) Reality is described through models. For example, the model of particle physics (Wiener et al, 2017) [12]
2) Models describe only some parts of reality and only to a certain degree.
3) The quality of a model depends on [8]:
   a) the number of phenomena it describes.
   b) how accurately such phenomena are described.
4) Given a certain phenomenon, the accuracy of the model in describing it is assessed according to the degree of agreement between model predictions and experimental observations.
5) Experimental observations must be collected to assess the quality of a model
6) Dealing with experimental measurements requires specific mathematical tools called statistics
7) Statistics does not provide scientists with the exact value of the measured quantities but uses probability to give only estimates of the value and of the uncertainties associated to such values.
8) Phenomena that are particularly difficult to observe need many experimental measurements to provide more reliable estimates
9) Once the bins are appropriately chosen, the histogram of many repeated measurements of a constant (i.e. not changing in time) physical quantity resembles a bell-shaped figure
10) According to statistics, if the number of repeated measurements of the same constant values is infinite, the histogram is becomes Gaussian (normal) distribution
11) The mean of a Gaussian distribution is the central value of the Gaussian curve and gives the most “reasonable” estimate of the constant physical quantity that is measured
12) The standard deviation of a Gaussian distribution gives the extent to which measurements are spread about the mean (68-95-99.7 rule)
13) In particle physics a new particle is officially discovered only when the distance of the mean value of its mass (in terms of energy) is more than 5 standard deviations from the background value

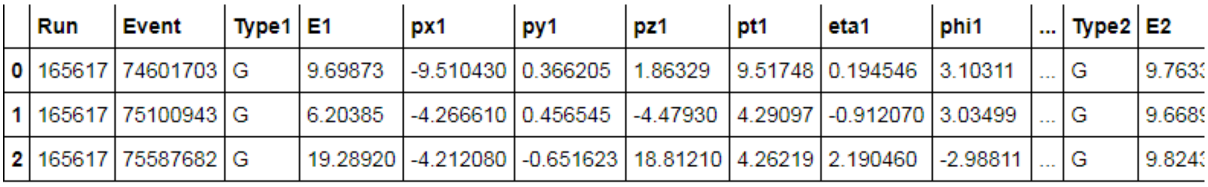
14) Collisions between particles and/or systems of particles are used to provide enough energy to the elemental particles so that they can interact and form new particles

Potential student conceptions & challenges

There is a broad research that focuses on understanding students' misconception about particle physics and data analysis. For instance, Tuzon and Solbes (2016) show that students recognise the actual concept of particle physics yet they have some misunderstanding with both new and classical model, the various interaction of forces including strong, weak, electromagnetic, and gravity as well as the charge of the particle[9]. However they are highly interested in learning particle physics and its social implications. Another research conducted by Gourlay (2017) reveals that students experience difficulties in understanding that muon and tau particles are leptons. They also consider that everything is made of quarks even though they already have adequate information about up, down, and strange quark as well as that electron is a lepton [10]. In addition, Woithe, Wiener, and Veken (2017) recommended "to use term 'transformation' instead of 'decay' to avoid students' misconception of the electron or positron as 'fragments' of the original neutron or proton [11]." This approach might help pupils to understand the probabilistic principles that govern high energy particle collisions.

The subject of particle physics evolves around experiments, therefore students must have an ability to analyze data to create histograms, draw conclusions and validate their predictions. In order to achieve this, students need to have background knowledge in mathematics and statistics to help them understand how the concept of particle physics changes with new discoveries. Cooper and Shore (2008) found that students are struggling to understand the meaning of variability of data in general as well as the interpretation of the data that are presented in a graph. Further, students have basic knowledge about how the distribution of data links frequencies with values on the horizontal axis but often confuse frequencies with data values.

When introducing data analysis of particle collisions in a classroom environment, students need to be shown how to extract the meaningful data from available resources. The use of data from a database is not necessarily a common practice in schools, therefore the process of extracting and using data may become a challenge for students. In our case, the data files contain a table of values displaying different measurements of particles after a collision took place. Confusion might result from the fact that the rows represent characteristics of a measured particle and columns are the characteristics that are measured (fig 2.). Usually, pupils write their data in the opposite way (fig 3.)



	Run	Event	Type1	E1	px1	py1	pz1	pt1	eta1	phi1	...	Type2	E2
0	165617	74601703	G	9.69873	-9.510430	0.366205	1.86329	9.51748	0.194546	3.10311	...	G	9.763
1	165617	75100943	G	6.20385	-4.266610	0.456545	-4.47930	4.29097	-0.912070	3.03499	...	G	9.668
2	165617	75587682	G	19.28920	-4.212080	-0.651623	18.81210	4.26219	2.190460	-2.98811	...	G	9.824

Fig 2. Columns represents characteristics that are being measured. Rows represent a single 'event' - a particle which properties of energy, momentum, type are being measured by a detector.

Independent variable	**Dependent variable**				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Measurement 1					
Measurement 2					
Measurement 3					
Measurement 4					

Fig 3. Simple data table commonly used in high school to organize the data from the measurements.

Helpful material and resources

Students' activities:

http://neutrino-classroom.org/TeachersGuideJuly2015/NeutrinoClassroomTeachersGuide-EditedJuly2015.pdf - Particle physics activities for high school physics students.

http://slideplayer.com/slide/8518655/ - Use of Cosmic Ray eLab to teach the research process.

http://www.i2u2.org/elab/cosmic/home/project.jsp - High school students use cutting-edge tools to do scientific investigations.

References:

[1] https://github.com/cernitw207/cerrnitw2017: this folder contains all the data, instructions and links for the task.

[2] https://github.com/cms-opendata-education/cms-jupyter-materials-english : further steps in data analysis of particles' collisions (plotting histograms, calculation of invariant mass,further statistics).

[3] https://scool.web.cern.ch/ CSV data files and other teaching resources.

[4] https://www.continuum.io/downloads download Anaconda (comes with many programming frameworks) and Jupiter Notebook that is recommended framework for the task.

[5] https://www.python.org/downloads/ download Python 3 for data analysis (reccomended).

[6] https://www.learnpython.org/en/Basic_Operators basic introduction to Python (contains many useful tutorials).

[7] http://opendata.cern.ch/ education and research resources provided by CERN.

[8] Qualities of a good model: https://www.learner.org/courses/essential/physicalsci/session2/closer1.html

[9] Tuzon P, Solbes J. Particle physics in high school: A diagnose study. Plos ONE. 2016; 11(6):1-9. doi: 10.137/journal.pone.0156526.

[10] Gourlay H. Learning about A level physics students' understanding of particle physics using concept mapping. IOP Science Physics Education. 2017; 52: 1-8. doi: 10.1088/1361-6552/52/1/014001

[11] Woithe J, Wiener G, Veken, F. Let's have a coffee with the standard model of particle physics. IOP Science Physics Education. 2017; 52: 1-9. doi: 10.1088/1361-6552/aa5b25.

[12] Wiener G, Schmeling S, Hopf M. Introducing 12 year-olds to elementary particles. IOP Science Physics Education. 2017; 52: 1-7. doi: 10.1088/1361-6552/aa6cfe.

Best practice example

There are a few activities provided in the open data portal of CERN [7], in which students are given the necessary tools and steps to analyze the data obtained from the collisions. The students can create histograms and analyze how their shape changes when the width of the columns is changed. They can also fit gaussian functions to the invariant mass distribution in order to determine the mean invariant mass of some of the decaying particles, as well as the standard deviation of the distribution and, therefore, their lifetime. However, in order to understand well these activities, the students need a strong background in mathematics and particle collisions.

On the other hand, two summer students at CERN, Henna Silvennoinen and Mira Tenguall, showed us an alternative and very user friendly data analysis program developed by them.
That allows a simpler analysis of the data. We thus decided to create an activity using this program, in which students work on simpler concepts of data analysis, and for which the level of understanding of the processes in particle collisions is minimal. Besides, it introduces students to the coding language Python. Students don't need to be familiar with it, but with the activity they will learn the basic characteristics of coding language.

The activity combines knowledge of physics, mathematics and the use of Python programming language [1,4,5]. The data used contains information about the two muons detected after the decay of a D0 meson produced in a proton-proton collision. The aim of the task is to calculate the energy of each muon using the relativistic formula $E^2 = p^2 + m_0^2$, and compare it with the value of the energy provided in the table (which has been measured with the detector). In principle it is similar to what has been done so far by other teachers [2] and is a small introduction to their work (calculation of invariant mass). The step by step instructions can be found in ‘energy calculations’ file [1]. In order to complete the task, pupils have to download the real CERN data from[1] (csv file), install Jupiter Notebook [4] and Python 2 or Python 3 [5] on their computers. Further instruction can be found in the link provided. [1]

Students will be first required to visualize the data processed in the detector. The table of values is probably much larger and contains much more information than the tables students are used to use (containing usually one column for the independent variable of the experiment and several columns for the different trials of the measurement of the dependent variable). Therefore, the first step should be explaining to students the type of information given in the table. This problem was illustrated earlier in Fig 2 and Fig 3.

The second step is to calculate the magnitude of the momentum of one of the muons in each collision, using the values of the three components given in the table. The total linear momentum corresponds to the square root of the sum of the squares of the three components (three-dimensional vectors): $p = \sqrt{p_x^2 + p_y^2 + p_z^2}$

This value is then used to find the energy of the same muon using the relativistic formula relating energy and linear momentum. Students will at the same time add a column in their table, where each row will display the calculated energy for each collision.

In order to compare it with the value of the energy measured in the detector, the students will create another column with the value of the difference between the two energies, and then plot a histogram in order to visualize the difference in energy for each of the collisions.

The instructions found in ‘energy calculations’ file show the desired outcome of the task, where pupils use the data to calculate relativistic energy and then compare their results with the table. This could give them an idea of how scientists verify a formula. This activity could be followed by either: calculation of invariant mass [2] or creation of a new activity where pupils use the relativistic energy to calculate the transverse momentum.

SG6 Antimatter

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Curriculum & classroom connections

The potential topics to introduce antimatter:

- astrophysics/star evolution & Big Bang
- conservation laws (conservation of lepton number, conservation of momentum)
- future energy sources: fusion
- medical imaging (PET-scan)

In the Big Bang Theory, the students learn the transformation of energy into matter and antimatter. They also understand how a small difference in the amount of matter and antimatter very early in the history of our universe led to the disappearance of antimatter. They become aware that the question of why our universe is composed of matter is still one of science's unsolved mysteries. The students would be aware that energy and mass are interchangeable quantities (that they can be transformed into each other) and, energy is also quantized in particles called photons.

Antimatter is a common concept found in many works of science fiction. If antimatter could be produced more quickly and economically, it would enable aerospace engineers to revolutionize space travel allowing interplanetary travel or possibly interstellar travel. Aerospace engineers are specialized engineers who design aircraft and spacecraft. Another application would be to use antimatter energy to produce electricity for humans' daily needs. A medical application of antimatter is used to understand how positrons are used in a PET scan.

Individual teaching practices:

Alexia: In Malta, antimatter is not taught directly, but indirectly through different application. Such as discussions on the Big bang theory and the use of Positron Emission Tomography (PET scans). It is then revised at a later stage where students explore the positron as an example of antimatter and the prediction of the neutrino and antineutrino at an advanced level of their studies. However, their experimental confirmation is not expected.

Maureen: In Colombia, the secondary school is divided into two phases. The first is called Media and the second, which is the object of our interest, is called Vocational Media. In the second phase the age range is approximately 15 to 17 years old. Students should study the main topics of classical physics with some degree of mathematical formalization. The Ministry of Education of Colombia, requires that curricula should have the following topics: mechanics, fluids, thermodynamics and electromagnetism.

Mehmet: The topic has not been taught in Turkey but we had change in the curriculum that will take effect this school year. The topic of big bang theory and the origin of universe will cover particle physics, matter and antimatter.

Guus: Particle physics (i.e. neutrino's), Feynman diagrams, Conservation laws (i.e. conservation of leptonnumber), Medical imaging: PET Scan

One of those connections can begin when addressing the questions 'What is matter?'. This as a prerequisite for answering this question. This question can be included in the moment of studying the states of matter in fluids and thermodynamics. The teacher can orient the class towards the standard model, in order for the students get an idea about electron, neutrino, up quark and down quark. This aim is to introduce the concept of antiparticles but before students must have an idea of the concept of charge which is also in the curriculum.

Key ideas

For meaningful instruction to begin, any topic must start off from a point that is familiar to the students for them to be able to make a connection. The two most common scenarios that students are aware of include the Star Trek movie and a more recent development was the Angels and Demons movie based on the book of Dan Brown, which even features footage taken at CERN itself. However, this alone is not sufficient and a knowledge of the basic principles of particles physics is required by the students to proceed onto the concepts of antimatter, with an in depth explanation of the properties of the elementary particles. Here, it would benefit the students if a concrete definition of antimatter is determined.

Simply put, antimatter is just matter which carries opposite charge and quantum spin of its counterpart [1]. All known elementary particles have their corresponding antimatter partner and some particles are their own antimatter particle (eg. the photon).

Given the mysterious connotation associated with antimatter, the students might be interested in the production and detection of these delicate particles. Contrary to popular belief, antimatter was detected quite some time ago by Carl Anderson in 1932, and since then a series of other antiparticle discoveries were made. We now live in an age where antimatter can be produced, stored and experimented on. By accelerating particles to high enough energies, their collisions result in the production of antiparticles. Magnets then filter out the antiparticles from the particles which are also produced in the collision.

The process of annihilation upon contact could be introduced to students, and the challenges present in storing the antimatter could be explored. Antimatter needs to be stored in a trap that suspends them in a combination of a vacuum, an electromagnetic field and a magnetic field. Following this, the next step would be to introduce students to an antiatom (such as antihydrogen) which is produced but is more complex because of the challenges that are present, preventing the binding of the positron to the antiproton. It might be surprising to students to explore the different antimatter facilities scattered around the world.

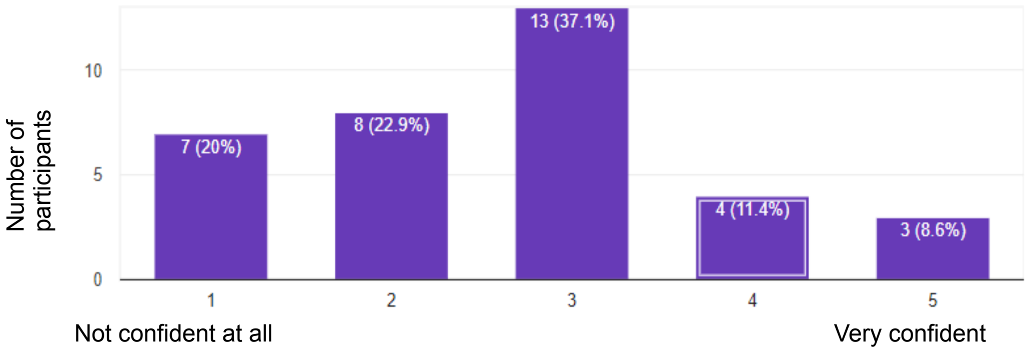
Finally the students can now explore the applications of antimatter and how studying such particles can benefit both science and the general public. As an extension for discussion, students could be introduced to the big questions that are still unanswered such as the mystery of the origins of our universe and the dissymmetry that is observed. Answering these questions would shed more light on the crucial beginnings of our universe.

Potential student conceptions & challenges

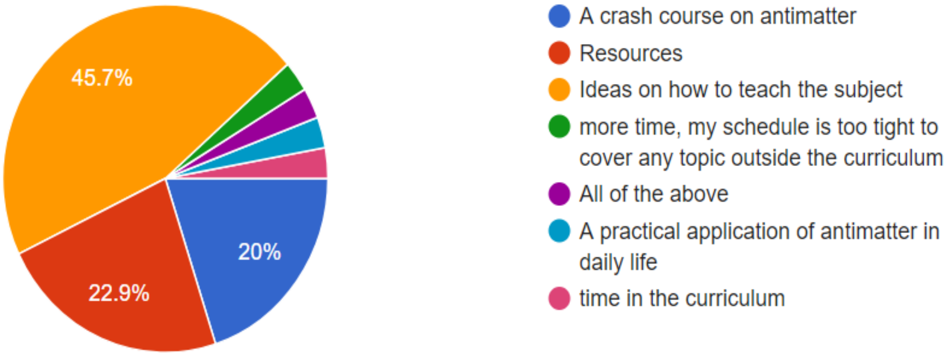
Before going into conceptions and challenges some heard misconceptions are mentioned. Asked for whether they know what antimatter is and/or does, the following answers were heard:

- It propels the Enterprise
- It’s the future source of energy
- It can kill the pope
- Parallel universes are made of it
- It’s Dark Matter
- It’s a Black Hole!
- It falls up

Antimatter is an abstract topic and this usually impedes students understanding of the topic. The subject title in itself has a mysterious connotation and it can easily conjure up incorrect interpretations of the subject. Furthermore, students may create false ideas as a result of the mystery that is attached to antimatter. For example, they might think that antimatter and dark matter are synonymous and interchangeable. They could also assign a colour to the particles and in their minds they might think that they are black. We cannot exclude the possibility that students might imagine antimatter to be an entity that exists outside of our world, completely detached from us. Students might also question what makes antimatter anti in the first place. The prefix suggests a property of matter that becomes opposite, so teachers have to be prepared to answer these questions, and with confidence. After conducting a short survey for Physics teachers on various social platforms, we found that out of a humble total of 35 responses 20% of the participants do not feel confident at all at teaching antimatter. For successful instruction in the classroom, the teacher should feel confident in the subject and have enough resources at his/her disposal.



The mentioned misconceptions will make the teaching of the topic more challenging and these same challenges must be addressed for a smoother learning process. Teachers feel more confident in teaching the subject when they have access to teaching ideas and resources for the subject. Therefore, making resources more readily available, making teachers less intimidated by the subject and more comfortable with teaching it.



Currently, there is no research available on high school student's conceptions on antimatter since we have not found a curriculum that includes the topic of antimatter exclusively. However to be able to discuss antimatter first we need to talk about matter, and this topic is included in chemistry and physics curricula. There is research about student's ideas on matter, and these can be classified in levels for example:
Students describe structures without the use of the particle concept. They consider matter as dividable but continuously build[2].
Students understand particles as entities embedded in matter between the particles is the actual substance. Students are not able to use their perception of particles to explain the structure of matter [3].
Students understand particles as a building brick of matter and that there is nothing between the particles [4]. These particles are often described as the "last divisible unit" that is why they are often described with macroscopic properties[5].
Students are able to describe particles with the use of a differentiated atom model (e.g. nucleus-shell, shell model)[6]. They differentiate between atoms and molecules and can distinguish between different bond types[7].
Students are able to describe and to explain the structure of complex molecules[8]. They are able to explain why specific interactions in a system of particles occur[9]. An overview of the research on students' concepts of matter can be found here: Understanding Matter - A Review of Research on Students' Conceptions of Matter[10].

Helpful material and resources

As we have seen, one of the most important obstacles for the implementing antimatter the classroom is teacher confidence in the subject, but increased resources and training in this area would encourage teachers to introduce more modern physics in their classroom. Therefore, we searched for resources that will support teacher learning and materials to be used with students and came up with two separate lists.

Teacher Resources

Title	Description	Link
What is Antimatter?	Fermilab scientist Don Lincoln describes antimatter and its properties. He also explains why antimatter, though a reality, does not pose any current threat to our existence!	https://www.youtube.com/watch?v=en2S1tBl1_s
Antimatter in the Lab	Dr Rolf Landua from CERN speaks about trapping antiprotons, antihydrogen, and applications of antimatter.	http://videolectures.net/cernstudentsummerschool09_landua_al/
Published material	Frank Close, AntiMatter, Oxford University Press..	https://www.amazon.com/Antimatter-Frank-Close/dp/0199578877
Antimatter	The CERN website makes a good abstract about antimatter, it include the following topics: the story of antimatter, the antiproton decelerator and antimatter experiments at CERN	https://home.cern/topics/antimatter

Students Resources

Title	Description	Link
CERN Anti-matter Teaching Module	The most comprehensive and reliable resources found are that of Terrance Baine found on the CERN website (Blaine, 2012). They are comprehensive as the material included is an entire teaching module consisting of eight PowerPoint presentations on the basics of antimatter that target an audience aged 14-15 years. It also includes background materials for teachers and two extension topics should the teacher wish to extend the topic further. Given that this resource is made available by CERN confirms its reliability. The aim of this resource is to make the subject of antimatter a regular participant in schools curricula by encouraging both students and teachers in becoming more fluent in the subject. This supports the notion for modern science to have a more active role in the curricula by helping teachers gain more confidence in the subject. The module starts off with how antimatter features in science fiction to capture the student's imagination and then evolves to the science behind anti matter.	http://ippog.org/resources/2010/cern-anti-matter-teaching-module
What happened to antimatter?	Lesson by Rolf Landua, animation by TED-Ed. Particles come in pairs, which is why there should be an equal amount of matter and antimatter in the universe. Yet scientists have not been able to detect antimatter in the visible universe. Where is this missing particle? CERN scientist Rolf Landua returns to the seconds after the Big Bang to explain the disparity that allows humans to exist today.	http://blog.ted.com/physicists-from-cern-team-up-with-ted-ed-to-create-five-lessons-that-make-particle-physics-childs-play/

If matter falls down, does antimatter fall up? - Chloé Malbrunot	Particles come in pairs, which is why there should be an equal amount of matter and antimatter in the universe. Yet, scientists have not been able to detect any in the visible universe. Where is this missing antimatter? CERN scientist Rolf Landua returns to the seconds after the Big Bang to explain the disparity that allows humans to exist today. Like positive and negative, or debit and credit, matter and antimatter are equal and opposite. So if matter falls down, does antimatter fall up? Chloé Malbrunot investigates that question by placing two atoms — one made of matter, and the other antimatter — in the cockpit of a plane, ready to jump. What do you think will happen?	http://home.cern/about/updates/2014/10/teded-animation-asks-if-antimatter-falls
Particle guess who	A nice way to allow students to get familiar with antimatter, might be using the following card game: Along the way of introducing and teaching particle physics and antimatter, the card game will help students feel more comfortable with these physical concepts.	https://www.tes.com/teaching-resource/particle-guess-who-11417017
Fundamental Particles Card Game	These cards can be used for students to familiarize themselves with the particle and antiparticle and also to make the learning more fun.	https://www.tes.com/teaching-resource/fundamental-particles-card-game-a-level-physics-11031595

The Antimatter Factory at CERN is certainly inspiring and the animation, “If Antimatter Falls” from Chloé Malbrunot might encourage teachers to develop projects with their students, such as investigating if antimatter atoms experience gravity the same way as ordinary atoms do. Students may investigate the topic of antimatter online together with receiving a lecture from a university professor, and then make a plan of a possible project. Students could then present the layout of a proposed experiment for the measurement of the gravitational acceleration of antimatter as well as the processes of charge exchange production of antihydrogen. The proposed design of apparatus allows the insertion of a magnetic trap for H, which will be spatially separated from the region where the anti-atoms are produced. Then students may create an animation to represent the overall process which they will present to the other students of the school and possibly apply for the Beamline For Schools from CERN.
Making the equations and Feynman diagrams for electron capture and e^+-emission, students do find out that capture of an electron will give the same result as emitting a positron and v.v. It’s a perfect way of making them think about matter and antimatter, realizing that matter might be considered as anti-anti-matter and they learn reading, using and making Feynman diagrams.

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1. Institute of Physics, *Antimatter.* http://www.iop.org/resources/topic/archive/antimatter/ last visited August 18, 2017.
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3. Papageor-giou et al., 2010; Talanquer, 2009; Tsitsipis et al., 2012
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SG7 Cosmology

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Curriculum & classroom connections

Different country have different educational needs and level of development according to science evolution. Yet, many correlating aspects can be found between different country in different continents and it's curriculum. Three continents are being considered in this paper, America, Europe and Asia, being the countries of Brazil, Dominican Republic the representants of America, Bulgaria and Ukraine of Europe and Japan of Asia.
From all these different curriculum we have the following table:

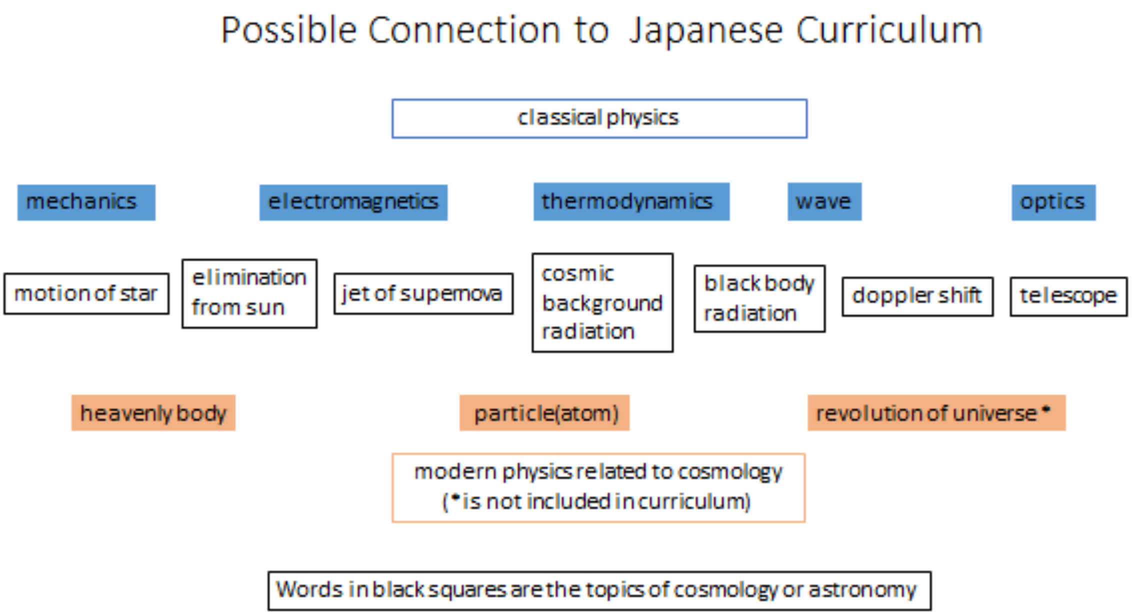
Continent	Country	Presence of Cosmology in the curriculum	
		Year of education	Presence of Cosmology
America	Brazil	University	Modern Physics course (board range, not focused on Cosmology)
	Dominican Republic		
Europe	Bulgaria	VII to XII*	Physics and Astronomy (dedicated courses) - including Cosmology
	Ukraine	3º year of High School	Astronomy (dedicated course)
Asia	Japan	University	Cosmology class in Physics course

*The years VII - XII in Bulgaria correspond students from ages around 11 - 17.

Considering the different curriculums that every country has, there's a apparent compatibility between the japanese, brazilian, bulgarian and dominican republic curriculums. In all these countries, there is no dedicated part of the curriculum for Cosmology topics, only a very short time to work all the concepts on the end of the last High School year and in Dominican Republic, the topic is only considered in the university. Therefore, the way to approach the subject would have to be as fast and effective as possible, once the time available won't be more than some hours.
Another option for approaching it, would be spread the different topics relating to contents traditionally already present on the curriculum as the following table possibility:

Cosmology topics	Cosmology key ideas	Relation between the traditional and the Modern Physics topics
Universe Evolution	Universe Origin	Thermodynamics
	Star and galaxy evolution - Black Holes	Kepler's Law
		Gravitational Force
	Inflation of the Universe, Red Shift and telescopes	Optics
	Present and end of the universe	Star and Galaxy evolution - Black holes
Particles	Cosmic Rays	Nuclear Physics
	Atoms fusion	
	Photoelectric effect	
	Standard model	
	Detection Technology	Photoelectric effect
Relativity	Special and General Relativity	Galilean Relativity

The following scheme shows a possibility of how to relate and apply these in the classroom acordingly to the japanese curriculum



Possible Connection to Japanese Curriculum

classical physics

mechanics

electromagnetics

thermodynamics

wave

optics

motion of star

elimination from sun

jet of supernova

cosmic background radiation

black body radiation

doppler shift

telescope

heavenly body

particle(atom)

revolution of universe*

modern physics related to cosmology (*is not included in curriculum)

Words in black squares are the topics of cosmology or astronomy

Key ideas

In every cosmic phenomenon and process there are manifestations of the fundamental laws of nature. On the basis of astronomical and astrophysical studies, natural and physical and mathematical knowledge is widely disseminated and generalized, principles of knowledge of matter and the universe are formed, the most important scientific generalizations, technical progress and the development of civilization are stimulated. Therefore, the course in Cosmology is an important components of the natural science in High school.

The purpose of the curriculum is the formation of general cultural competence, the scientific world outlook and the basis of the knowledge system in cosmology. Therefore, High School and teacher main goals and tasks may be said as being:

- provide general and specialized system knowledge of astronomy and astrophysics;
- to create conditions for the formation of skills and ability to conduct scientific research;
- to form skills of scientifically grounded thinking, logical and consistent expression of own thoughts;
- to develop communication abilities;
- to develop the ability to independently work with information sources, to systematize, generalize the information obtained and to use it.

The process of performing a task may not be endowed with a mathematical form. Problems with mathematical calculations should be offered only as much as their contents, once these calculations are really necessary. Also, it is not desirable the teacher to offer settlement tasks that do not include specific numeric data, once a formula in which no concrete content is put in, generates dissatisfaction to the student. Getting to the solution of the problem, is necessary to pre-understand the nature of this task, to show the necessity of using one or another formula and, which is also very important, explain the result and present it clearly. Generally, in control works, the definition of concepts should occupy a minimal place, the main thing - these are issues that, without requiring calculations, reveal an understanding of the essence of the phenomena or concept.

Among the topics and ideas to be worked about cosmology there are, for example, the determination of the parameters of the stars according to the Hertzsprung-Russel chart, beam speeds of sight; distances to galaxies for displacement of spectral lines and using the law of hubble.

The main goals when introducing the cosmology concepts to students are for them to having the following knowledge:

- General information of galactic astronomy;
- Elements of cosmology;
- Cosmological paradoxes and principles;
- Models of the universe;
- Fundamentals of astrophotometry and spectroscopy;
- Laws of equilibrium radiation;
- Basic information about the solar system;
- On the physical nature of the stars and the main stages of their evolution;
- The main sources of star energy;
- Physical content of the Hertzsprung-Russell chart.
- To solve the exercises on the red shift and the law of Hubble.

Potential student conceptions & challenges

Illustrate elements of the topic that might obstruct a successful introduction in the classroom: When considering introducing Cosmology topics in the classroom, there are some issues that may be raised related to the concepts that they already know, or misconceptions that might still resist formal education.

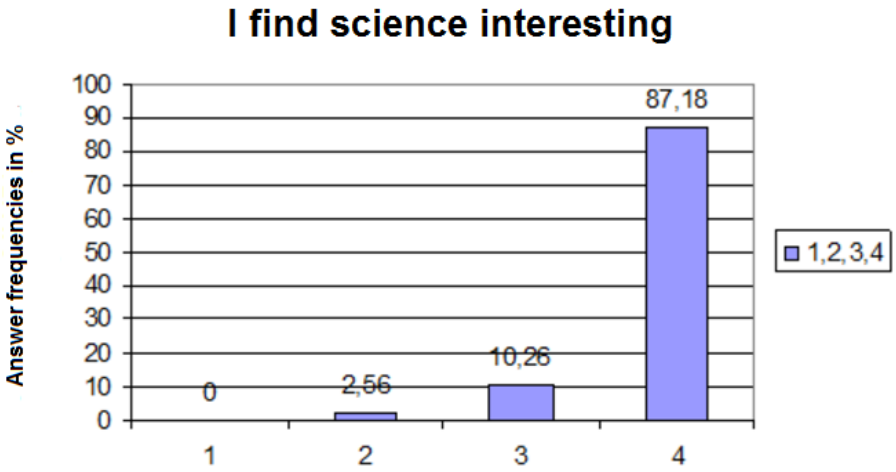
Considering the cosmology topics presented in table 1, we could consider the following difficulties for every topic:

Cosmology topics	Cosmology key ideas	Possibly difficulties (ideas that students have prior to learning the cosmology concepts)
Universe Evolution	Universe Origin	The idea of Big Bang being a literal explosion like the ones observed on Earth
	Star and galaxy evolution	The idea of a stable universe
	Black Holes	The idea of space and time as absolute and not a space-time
	Inflation of the Universe, Red Shift and telescopes	The idea of infinite universe
	Present and end of the universe	The idea of the universe having a begin but, being stable, no end
Particles	Cosmic Rays	The idea that fundamental particles can only be obtained in very elaborated equipment like the LHC
	Photoelectric effect	The idea that electrons may receive energy from light and be by freed from the atom
	Standard model	The idea that the proton in an elementary particle
	Detection Technology	The idea that calorimeters are only used on thermodynamics experiments
Relativity	Special and General	The concept of absolute referential

Not only the concepts above may make it difficult for the students to understand Cosmology topics, but also, there's a current lack of interest from the students related to sciences, as Linn, Bell and Davis (2004) put "One of the major educational problems at present is the alienation from the school and the lack of willingness to study, especially in the field of science/astronomy subjects." One of the possible approaches to call their attention to sciences, if the constructivist environment and the Inquiry Based Science Learning, focusing in research activities, formulation of hypothesis, performing experiments, analysing and discussing results.

Thus, the students come to the facts by themselves and give their suggestion concerning the relationships among them. They take the role of young scientists/ researchers. Linn, Davis and Bell (2004).give the following definition: "The research work could be defined as a conscious process for problem diagnosing, doing experiments and defining of alternatives, planning of research work, giving scientific research suggestions, looking for information, designing of models, discussing with classmates, forming of clear argumentation". This approach develops skills that will be useful lifelong for the young people.

Analysing the empirical data presented below, one can conclude that students are extremely motivated for learning based activities. The results are shown in percentages. For example 87.18% of the students answered by "Strongly agree" that they find science as interesting and just 2,56% expressed disagreement. A relatively high percentage 79.49% answered "Strongly agree" that learning Science would help them find a good job.

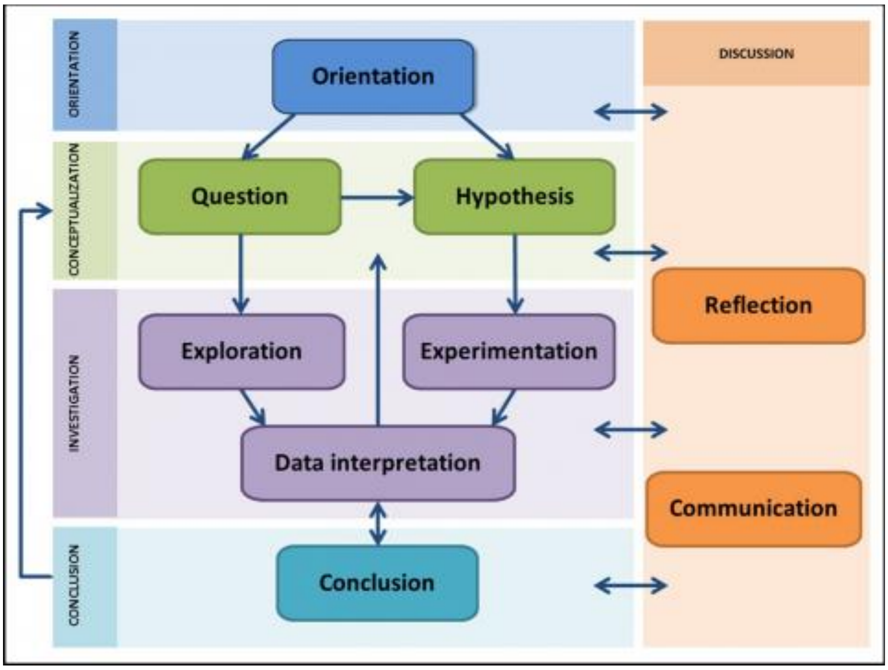


An Inquiry Learning Cycle to specify the consecutive steps of an inquiry learning process constituted by five main phases: Orientation, Conceptualization, Investigation, Conclusion and Discussion. All phases of the inquiry learning process are closely connected with each other and provide a structure aiming at increasing the efficiency of the learning activities.

In the first two phases of the cycle (Orientation and Conceptualization) the opportunity is given to the students to gather information on a research question, take notes and build hypotheses and questions they want to investigate. Appropriate tools (like concept-map templates, search software, scratchpads, hypothesis-builder, etc) to help students to work on their own can be provided by the teachers in the Inquiry Learning Spaces.

The third is the Investigation phase (which includes Exploration, Experimentation and Data Interpretation activities) in which students collect specific data and check whether a hypothesis is correct or not by conducting personalized experiments. Also, the students can gather experiment results and conduct guided interpretation of the collected data.

During the last two phases of the inquiry learning process (Conclusion and Discussion), the students learn how to write scientific explanations linking their hypotheses with the evidence collected during the investigation phase. Further, they are reflecting on their learning processes and outcomes, comparing and discussing them with other students. Teachers can evaluate learning results of their students and define further steps for the next classes.



Helpful material and resources

1.General information

- http://www.ted.com/talks/richard_dawkins_on_our_queer_universe
- https://www.youtube.com/watch?v=hUJfjRoxCbk

Experiments in cern related to cosmology or astrophysics:

- CLOUD https://home.cern/about/experiments/cloud
- CAST https://home.cern/about/experiments/cast
- Cosmic ray https://home.cern/about/physics/cosmic-rays-particles-outer-space
- Dark matter & dark energy https://home.cern/about/physics/dark-matter
- Early universe https://home.cern/about/physics/early-universe

2.Application

- https://getkahoot.com/
- https://www.socrative.com/

3.Material for classroom activities and information of students' programme:

- International Particle Physics Outreach Group www.physicsmasterclasses.org
- S'Cool LAB http://scool.web.cern.ch/
- Perimeter Institute
  https://www.perimeterinstitute.ca/outreach/teachers/class-kits
  https://www.perimeterinstitute.ca/outreach/teachers/multimedia-resources
  https://www.perimeterinstitute.ca/sites/perimeter-www.pi.local/files/NGSS%20Infographic%20March%202016%20no%20crops.pdf
- https://spaceplace.nasa.gov/classroom-activities/en/
- https://starchild.gsfc.nasa.gov/docs/StarChild/.../cosmology.html
- http://www.space-awareness.org/en/activities/1502/lets-break-the-particles/
- http://www.space-awareness.org/bg/games/disk-detective/
- encyclopedia.kids.net.au/page/co/Cosmology
- Quarknet data portfolio http://quarknet.i2u2.org/data-portfolio
- the community for cosmic rays in the classroom
  http://portal.opendiscoveryspace.eu/community/cosmic-rays-classroom-848307

4.Online lab

- Quarknet http://quarknet.i2u2.org/
- https://www.zooniverse.org/projects?discipline=astronomy&page=1&status=live
- http://portal.opendiscoveryspace.eu/content/hypatia-673571
- http://portal.opendiscoveryspace.eu/content/las-cumbres-observatory-global-telescope-673563
- http://portal.opendiscoveryspace.eu/content/chromoscope-676928
- http://portal.opendiscoveryspace.eu/content/multiwavelength-universe-677145
- http://www.schoolsobservatory.org.uk
- muon time dilation scenario: https://tinyurl.com/ybf3dvh5

5.Participation of students in experiment

- AMS http://home.cern/about/experments/ams

Best practice example

The use of experiments is very effective to perceive phenomena and understand models. Therefore, an example of best practice could consist in two parts:
1. Perceiving phenomena: Cosmic ray is appropriate for the topic of introduction of cosmology because tracks of cosmic ray are visible, experiment can be done in classroom and it can connect to many other topics. Shape of tracks explained by electromagnetics, and branches of tracks show nuclear interaction. Furthermore origin of cosmic ray is cosmological phenomena.
2. Understanding models: The Learning by doing method provides a very good opportunity to illustrate the topic. In this study, we present a very simple model made from handy materials "How to make a model of supernova". Students can paint the explosion of Cassiopeia A. on paper. The atoms are made of toilet paper and stained in different colors. The wool wave is demonstrated by a plastic cup and a bubble membrane.
Students are asked to make predictions on how galaxies form and evolve in the Universe. They will use the 'Galaxy Crash' tool to simulate the evolution of 2 disc galaxies over time, and see if the results match their predictions.

Finally, the students will search the data archive of the robotic Faulkes Telescopes and find observations of interacting galaxies. They will then try and use the ‘Galaxy Crash’ software to reproduce the images which they have found and draw conclusions on the initial conditions from which the interacting galaxies came from, and what they might expect to happen to the galaxies in the future.

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https://www.britannica.com/biography/Henry-Norris-Russell

SG8 Engineering in particle physics

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Engineering in particle physics comprises the challenges of designing and building particle accelerators, detectors and other auxiliary systems. The engineers must create new technological solutions which satisfy the physicists' requirements. They also have to maintain the infrastructure.
Engineering covers so many areas, but this document focuses on electrical systems, magnetic and optical devices, vacuum and cooling technologies.
This paper presents links between engineering and secondary schools science & technology curricula, and an example that uses the concept of superconductivity to teach students about electrical resistance and its dependence on temperature.

Curriculum & classroom connections

Engineering technologies involve most parts of typical high school physics curricula.
The following table highlights some of these connections:

Physics concepts	**Technologies**
Electrical field	Accelerating cavities
Voltage, current, power consumption	Electrical power systems
Resistance, superconductivity	Superconducting magnets
Magnetic field strength and lines, Lorentz force	Electromagnets and superconducting magnets
Reflection, refraction and total reflection	Optical fibers
Pressure	Vacuum systems
Temperature and heat	Cooling systems
Frequency	Radiofrequency and signals
Force, Torque and mechanisms	Electro-Mechanical and Civil engineering structures

Superconductivity is not explicitly mentioned in our curricula, but we believe it is worth teaching nonetheless. In our opinion superconductivity is an important technology and will become even more so in the future.

Key ideas

The aim is to introduce superconductivity, its applications and the engineering aspects of superconducting magnets to the classroom.
Superconductivity is the phenomenon when a material at very low temperature loses its resistance.
Typically conducting materials are not good superconductors but some non-conducting compounds on very low temperatures became superconductors.

At present this phenomenon is used to make electro-magnets which are more powerful than ordinary ones. For designing and making these magnets, engineers have to tackle different problems and overcome technical obstacles, for example:

- Finding the best materials for the wires,
- Cooling the whole system,
- Powering the installation,
- Managing the material contraction during the cooling,
- Controlling the forces at work during operation.

Handling all these issues requires different types of engineering: mechanical, electrical, material, civil etc.

Potential student conceptions & challenges

Many students do not have many conceptions about particle physics and superconductivity, since they probably have never come across it before. In addition, they don't know much about an engineer's tasks.

Superconductivity is not a part of everyday life, but it can be made interesting through applications in scientific research, medicine and so on.

The challenge is also to explain to the class what engineering involves. We will do so using superconductivity as an example.

Most schools do not have the necessary equipment to do experiments with superconductors, but online resources can be used instead.

Helpful material and resources

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Android apps: Superconductors Explain about different superconducting materials
10. AcceleratAR Augmented reality application showing how CERN accelerators work - Video

Best practice examples

Introductory comments for teachers:
CERN uses superconductors in its colliders. At CERN protons are sent through a circular tunnel and magnetic fields of high intensity are needed to guide the beam of protons in a tube in this tunnel. CERN colliders need magnetic fields of eight or even more Tesla. The limit for conventional electromagnets is two Tesla. Therefore, CERN has switched to superconducting coils to make the electromagnets more powerful. Of course, superconductors have their price: for instance, they only develop their qualities of superconductivity at extremely low temperatures. Engineers had to develop ways to cool the electromagnets and to make wires out of a superconducting material. Copper and other conventional conductors are generally unsuitable superconductors; therefore, a completely new material was used in the wires. Support systems for the collider had to be developed from scratch including the world's most powerful cooling system and the longest vacuum tube. Seen in this light, the superconducting magnets are only one small element in the biggest machine built on Earth.

First activity: resistance
Comment for teachers:
The following exercises are designed to be used in a regular classroom and they should all work without the support of laboratory equipment. The exercises can be used both for introductory purposes or to revise and

elaborate on known concepts. Especially, the first exercises dedicated to the introduction of electrical resistance and the definition of the different branches of engineering can also be used in groups of low achievers.

Material for students:
Where do we meet with resistance in everyday life?

copper wire, land line, electric kettle, electric plate on a stove, hot iron, grounding, earthing system

Group the above-mentioned objects into the following two categories:
high resistance wanted / low resistance wanted

Afterthought for teachers:
The aim of this exercise is to make students aware of the fact that resistance is wanted in some applications but a rather negative side effect in other circumstances. In land lines low resistance is sought for as it means power losses. This exercise leads to the next step in which the focus is on the effects voltage on minimizing power loss.

Second activity: examples for high voltage and low voltage surroundings

land lines in a local area, land lines as part of a national grid, motherboard in a computer, kitchen appliances, mobile phone, hair dryer, battery powered torch

Divide the examples again into two groups and compare your results with those of the whole study group.

Consider the following questions:

- Why is there high voltage at work in some applications but not so in others?

What is the price of high voltage? What is the price of low voltage? What are the respective advantages and disadvantages?

Third activity: superconductivity
Unfortunately experiments with superconductivity require liquid nitrogen, which can be hard to acquire, therefore we suggest watching a video to bring the experiment to class. For example the video for the standard experiment on superconductivity from BBC Four (2017).
Student activity:
Give the students some different graphs of resistance and temperature, including real conductors and superconductors, and ask them to identify the conductors and superconductors. Then they can go together in groups and explain their reasoning to each other. Then they get the correct solutions with reasoning.

Activity four: Engineering at CERN
Comment for teachers:
Engineering at CERN has helped create a machine that allows mankind to look at the smallest particles of our universe. The engineering involved is in contrast extremely large scale and often record breaking in size. Many students do not know what engineering is, so the following task is meant to introduce students to different areas of technology that various types of engineering deal with. All the areas mentioned here form a part of the Large Hadron Collider at CERN.

Student Material:
Categorize in terms of the type of engineering that is involved!
electrical engineering / material design - materiology / mechanical engineering / electronics / civil engineering

tunnel, superconducting electrical magnets, cranes to move heavy machines, electronic detectors, crystals for detectors, wires made of superconducting materials, coils for motors, pumps for cooling systems, electronic devices checking on the running machine.

SG9 Future particle acceleration projects

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Curriculum & classroom connections

This report on future accelerator projects is concerned predominantly with the Future Circular Collider and how it can be used as an engaging context to help achieve school curriculum objectives.
The obvious links between future accelerator projects and physics curriculum are the concepts of Lorentz force and relativistic effects such as mass dilation, as these concepts are fundamental to both particle accelerator technologies and to physics curricula around the world. For example the Australian curriculum requires that 'students understand transformation and transfer of energy associated with motion in electric and magnetic fields'; The Bavarian curriculum requires the students to "get to know and appreciate the achievements of large accelerators for the advancement of physics during the 20th century"; and in Mexico the topic of electromagnetic theory and wave mechanics is studied in senior physics. In Iran in recent years the educational system and textbooks have changed and these changes are still ongoing. The inclusion of more objective and practical examples such as particle accelerators and their applications in industry and medicine can improve students' perceptions of science especially physics.

It is suggested that in the classroom these curriculum objectives can be achieved through the use of comparative analysis, in which current technologies (LHC) are compared with proposed technologies (FCC); in particular, through the application of basic physics principles such as forces on charged particles in electric and magnetic fields, and relativistic mass dilation.
The topic of future particle accelerator projects can also be linked to curriculum statements that explore the use and influence of science in society. For example the Australian curriculum requires students to understand that 'international collaboration is often required when investing in large-scale science projects' and 'advances in scientific understanding often rely on developments in technology.' The Bavarian curriculum also includes the discussion of socio-political issues associated with large accelerators.
This context of science in society would be a good opportunity for students to practice core skills such as literacy, numeracy, communication and collaborative skills, and information technology skills.

Key ideas

1. Compare current accelerator technologies with proposed technologies by applying basic physics principles.
2. Understand that new scientific knowledge requires the development of new technologies.
3. Understand the importance of international collaboration when investing in 'big science' projects.

Potential student conceptions & challenges

1. Students might expect that a larger accelerator provides faster particles. Although particle energies in the FCC will be higher than ever before (e. g. in the LHC), particle speed is not increased dramatically due to relativistic mass dilation.

2. Students may have misconceptions about how fundamental science is conducted, having only been exposed to experimentation at a basic level. In particular students may not appreciate the need to create new technology in order to obtain new scientific knowledge.

3. Similarly, students may not appreciate the integral nature of international collaboration in ‘big science’ projects’.

Helpful material and resources

Resources for FCC

https://fcc.web.cern.ch/Pages/default.aspx (FCC webpage)
http://cds.cern.ch/record/2262019 (Physics at its limit, Michelangelo Mangano, CERN courier)
https://cds.cern.ch/record/2150225 (CERN animation)

Other Future Accelerator Projects:

http://cepc.ihep.ac.cn/ (Circular Electron Positron Collider CPEC)
http://clic-study.web.cern.ch/ (Compact Linear Collider CLIC)
https://www.linearcollider.org/ILC (International Linear Collider ILC)
http://hilumilhc.web.cern.ch/ (High Luminosity LHC)

General
https://cosmosmagazine.com/physics/after-the-lhc-which-will-be-the-new-king-collider
https://cds.cern.ch/record/2150225 (panel discussion on the future of particle accelerators)
https://en.wikipedia.org/wiki/List_of_accelerators_in_particle_physics

Best Practice – Applying Physics Principles

The table below provides a comparison of key physical quantities for the LHC and the FCC-pp. Teachers could make use of this table to construct problems related to Lorentz force and Relativistic effects. Two examples with solutions have been provided.

Physical property	**LHC**	**FCC p-p**
energy per proton	$E_{kin} = 7\text{TeV} \approx E_{tot} = \gamma \cdot E_0$	$E_{kin} = 50\text{TeV} \approx E_{tot} = \gamma \cdot E_0$
Lorentz factor	$\gamma = \frac{E_{tot}}{E_0} = \frac{7 \cdot 10^{12}\text{eV}}{938 \cdot 10^6\text{eV}} = 7.5 \cdot 10^3$	$\gamma = \frac{E_{tot}}{E_0} = \frac{50 \cdot 10^{12}\text{eV}}{938 \cdot 10^6\text{eV}} = 53 \cdot 10^3$
speed of proton	$v = \sqrt{1 - \frac{1}{\gamma^2}} \cdot c = 99.9999991\% c \approx c$	$v = \sqrt{1 - \frac{1}{\gamma^2}} \cdot c = 99.99999998\% c \approx c$
Time T for completing one cycle	$T = \frac{2\pi r}{c} = \frac{27\text{km}}{3.0 \cdot 10^5\text{km}}\text{s} = 0.090\text{ms}$	$T = \frac{2\pi r}{c} = \frac{100\text{km}}{3.0 \cdot 10^5\text{km}}\text{s} = 0.33\text{ms}$
relativistic mass of the proton	$m_p = \gamma \cdot m_0 = 7.5 \cdot 10^3 \cdot 1.67 \cdot 10^{-27}\text{kg} = 1.25 \cdot 10^{-23}\text{kg}$	$m_p = \gamma \cdot m_0 = 8.90 \cdot 10^{-23}\text{kg}$
mean centripetal force F_C	$F_C = m_p \frac{v^2}{r} = 2.6 \cdot 10^{-10}\text{N}$	$F_C = m_p \frac{v^2}{r} = 0.5\text{nN} \approx 500\text{pN}$
mean magnetic flux density B	$F_C = qvB \Rightarrow B = \frac{F_C}{qv} = 5.4\text{T}$	$B = \frac{5.0 \cdot 10^{-10}\text{Ns}}{1.6 \cdot 10^{-19}\text{C} \cdot 2.998 \cdot 10^8\text{m}} = 10.5\text{T}$

Example1: Relativistic mass

In the LHC, each proton has a target energy of 7 TeV. Its corresponding (relativistic) mass is then

$$m = \frac{7 \cdot 10^{12} \cdot 1.6 \cdot 10^{-19}\mathrm{J}}{\left(3.00 \cdot 10^{8}\frac{\mathrm{m}}{\mathrm{s}}\right)^2} = 1.2 \cdot 10^{-23}\mathrm{kg}$$

This is four orders of magnitude more than the mass of a resting proton ($1.67 \cdot 10^{-27}$kg).
The future FCC will accelerate protons to energies of 50 TeV. Calculate the relativistic mass of the proton in the FCC.

Solution:

$$m = \frac{50 \cdot 10^{12} \cdot 1.6 \cdot 10^{-19}\mathbf{J}}{\left(3.00 \cdot 10^{8}\frac{\mathbf{m}}{\mathbf{s}}\right)^2} = 8.9 \cdot 10^{-23}\mathbf{kg}$$

Example2: Lorentz force

a. Calculate the value of the centripetal force which keeps the proton on its trajectory in the FCC (given it is a perfect cycle) and compare with gravity.

   Solution: $F_C = m_p \frac{v^2}{r} = 0.5\mathrm{nN} \approx 500\mathrm{pN}$, gravity acting on proton: 0.000000000000016 pN

b. Find out the required value of magnetic flux density in order to achieve this centripetal force:

   Solution: $F_C = qvB \Rightarrow B = \frac{F_C}{qv} = \frac{5.0 \cdot 10^{-10}Ns}{1.6 \cdot 10^{-19}C \cdot 2.998 \cdot 10^{8}m} = 10.5T$

c. The FCC project study shows that a magnetic flux density of even 16 T is required. Why do you think that the value calculated above might be too low? Do some research on the internet if the FCC is going to be a perfect circle - or will there be linear parts for acceleration and experiments?

d. The LHC today uses magnets which provide a magnetic flux density of up to 8.3 T.
   What challenges do you imagine could arise when aiming to double the value of flux density?

Best Practice – New science, new technology

A suggested task is for student groups to research different accelerator projects – past, present and future and complete specification tables for them. A list of accelerators could be provided (see resource list).

Another learning experience is a team work task, in which student groups are placed in the role of scientists preparing and delivering an FCC Project Proposal to a board of politicians. Groups could be guided to consider questions like ‘What fundamental science will the new project be studying? What applications may arise from the project? What are the technical problems that need to be overcome? An IT skill component could be added to this task by requiring teams to film and edit their presentations. It is also suggested that a resource list could be provided for students.
A smaller scale learning activity involves students reconstructing a scale diagram of the FCC on a local map. This would involve manipulation of the circumference formula and interpreting scales. It would also provide students with a better indication of the scale of this proposed project.
Another smaller scale task could relate to the mode of transport that technicians use to travel along the accelerator tunnel. Technicians use bicycles to move around the LHC tunnel. The FCC would require an improved system as the distances involved would be too far. A Student task could involve the design and presentation of their solutions.

Best Practice – International Collaboration

The CERN organization is a very good example of the importance of large scale collaboration in science, and could be used by teachers to help students understand the concept.

The SESAME project is another collaborative project based on the CERN organizational model that has brought together countries of the Middle East despite ongoing tensions. The member states are Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, The Palestinian Authority, and Turkey. This could be used by teachers as an example of the non-scientific benefits of international collaborations. The following question could be posed to students: *Apart from providing new scientific knowledge, what do you think is another important aspect of the SESAME collaboration between these countries?* This question would suit a written individual response followed by peer discussions, then presentation of a group response to the class.
Another task involves students identifying another current scientific challenge that might benefit from an international collaborative project, and justifying their responses