HST2022

Study Groups

FINAL REPORTS

CONTENTS

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Particle Accelerators

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1) Key ideas

- Ionization of an atom enables the acceleration of the ion
- Electric fields cause the acceleration of the ion
- Magnetic fields cause the circular motion of the ion
- Scale of mass and energy units
- Scale of velocity
- Introduce particle physics while teaching these topics

2) Best practice example

Bringing particle physics into the high school classroom can be challenging. As few curriculums directly address particle physics, it is important to expand on classical concepts to relate them to this modern branch of physics. The topic, however, can be frustrating to students because of its more abstract nature. Providing concrete examples and appropriate analogies (even though Jeff is not a fan!) can help students begin to create an accurate model of the tiny universe surrounding them. Allowing students to predict results of experiments and demonstrations is a method that can cement concepts for students and allow them to make those connections. Whiteboarding predictions and results followed by student-led discussions grants students the opportunity to express their ideas and open them up to peer evaluation.

3) Helpful material and resources

The Particle Adventure https://particleadventure.org/

Engineering at CERN

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1) Key ideas

Including Engineering within the curriculum provides opportunity for students to develop skills in problem solving, critical thinking, creativity/innovation and collaboration. These are essential life skills in being an engineer and are transferable to all subject areas. Actively being creative is the big key here. The students will have to learn that it's normal to make a first prototype, see that it's not optimal, go back to the drawing table and adjust! It's just part of a great cycle. We think presenting projects with an engineering context could help understanding the subtleties of this kind of scientific career.

At the same time, they will learn to deal with other humans, which is a big part of engineering. Apart from all the scientific content, they will also learn to listen to each other's ideas, have the courage to propose new and different point of views and accept the force and weakness of everyone in the team.

What we hope to do by integrating more engineering in high school is to broaden the point of view of scientific careers that are available. We want the students to discover that if they enjoy dismantling objects, program games or web applications, construct elaborate structures with legos… there are interesting career paths for them.

Of course, when we talk about engineering, we must absolutely promote the place of women! Things started to change in the last decade, but there is so much more to do to make female students believe they belong in these different fields.

CERN is very much looking towards the next generations of engineers because the new challenges they face will require great expertise and creativity. By talking about CERN in the classroom and how they solved problems they encountered in the past, we hope to ignite an interest and passion for engineering.

2) Best practice example

The design process can be used within all content areas of physics and can be easily put in the context of problems that have been solved at CERN. Getting the students to be hands-on with designing, building and creating prototypes with basic equipment (straws, popsicle sticks, rubber bands etc), or using Fab Labs or 3D printers to build their designs enables them to 'become engineers'.
For example, use a problem that engineers had to solve in the building of CMS, ATLAS or LHC and get students to develop their own solution to the problem, build a prototype to test and then reflect on their design. Example two: Use minecraft to build parts of the LHC and Detectors in groups.

3) Helpful material and resources

https://discovere.org **!** Many STEM activities from all ages to explore the engineering mindset. They present the Engineering design process.

https://www.swissinfo.ch/eng/behind-the-scenes-at-cern_meet-the-engineers-who-make-machines-for-understanding-the-universe/44034840 Article about the engineers who work at CERN and the challenges they encounter.

https://alumni.cern/news/404136 Article written by Simone Gallegari that explain the best approach in engineering at CERN for a successful project. The article also contains some exemples of problem/solution encountered.

https://home.cern/science/engineering General informations about Engineering at CERN

https://cerncourier.com/a/viewpoint-lessons-from-the-accelerator-frontier/ Lessons from the accelerator frontier

https://cerncourier.com/a/the-ls2-vacuum-challenge/ The LS2 Vacuum Challenge

Medical Applications of Particle Physics

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1) Key ideas

There are some key ideas to consider for meaningful classroom instruction. Then, students will be able to comprehend the connection between particle physics and medical application. By focusing on the following basic terms and giving more information about them, they make the students aware of the connection between particle physics and medical applications.

- Types of radiation and their penetration depths
- Medical imaging techniques
- Therapies
- How each technology works
- Rationale for use
- Effects of X-rays on organisms
- Possible effects of studies, done in SRCs (Scientific Research Centers), on science and technology
- Medical applications represent the largest use of particle physics!
- Students need to know why it is important - inspiration and career choices
- Advances in scientific technology - early detection, targeted treatment
- Connections to Biology - cancer, effect of radiation on organic matter.

Imaging	Therapy
Detectors	Accelerators
• X-ray (and contrast fluid) • Nuclear diagnostics • Magnetic Resonance Imaging (MRI) • Computed tomography (CT) • Positron emission tomography (PET) • Single-photon emission computed tomography (SPECT) • Echo	• Radiation therapy • X-ray tube • Particle therapy

2) Best practice example

CERN operates on three major domains: accelerators, detectors and computing. Manjit Doosanjh, in her lecture at the HST 2022 programme last week, pointed out that in fact she saw there were four pillars, and the fourth being collaboration. We agree that collaboration is indeed crucial in scientific research. To this end, developing an interdisciplinary unit between science disciplines could introduce the idea that science is a group work and to give students an opportunity to study Medical Application of Particle Physics at a greater level. In such a unit, discussions on topics like FLASH for cancer treatment could inspire the new generation to participate in such projects to make them a reality.

A key best practice example came from experiences teaching medical applications of particle students to physics. Understanding the different types of imaging was a main concern highlighted by the study group and surveyed students. To make this clearer, students are given a partially filled table to lay out each of the techniques, the physics involved, important applications, and advantages and disadvantages. Students use a provided data sheet to fill in the blanks. This results in a very useful study resource and greater understanding of the differences between imaging techniques.

3) Helpful material and resources

The following list provides a number of helpful materials and resources that may assist students and teachers with the topic of medical applications of particle physics.

- cern.ch/PER
- Natuurkunde Overal (Robert Bouwens, Noordhoff uitgevers), BINAS
- Presentation by Manjit Doosanjh
-https://www.symmetrymagazine.org/article/november-2013/how-particle-physics-can-save-your-life
-https://indico.cern.ch/event/505656/contributions/2178989/attachments/1286957/1914803/Medical_applications_-_Sparsh.pdf
-https://iopscience.iop.org/book/978-0-7503-1444-2/chapter/bk978-0-7503-1444-2ch1#bk978-0-7503-1444-2ch1s2
- https://seeiist.eu/
- https://enlight.web.cern.ch/media/videos/virtual-particle-therapy-centre

Particle Detectors

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1) Key ideas

To begin with, us! We are from a huge range of cultures and have an even wider range of teaching experience. In discussing the connections to our individual curriculums we agreed that detectors, for example the camera, the eye and the Geiger-Muller Tube, are featured in all of our curriculums but maybe just not on the scale and complexity of those that we find at CERN! Some ways you could link CERN's particle detectors to your curriculum to give context; When teaching scale discuss the smallest and largest things known to us, link density to the material choices in the hadronic calorimeter and when teaching about the CMB tell students that the detectors are often still running during shutdown periods to understand what background there is affecting their detectors. The possible links are endless! Research, from the Institute of Physics, shows us that pupils, especially girls, are more engaged when they are shown possible careers alongside the content they are learning. Introducing the range of fantastic speakers we've had this week who work on, or who's work depends on, detectors, would be one great way to do this with a personal touch.
Challenging factors for effective particle physics teaching can be classified into two broad classes: Teaching challenges and student-centered potential challenges. The former class mainly concerns challenges related to connecting simple particle detectors to industrial (usually large-scale) detectors. The latter class comprises problems related to; naming particles at the atomic and subatomic level (and below), differentiating between elementary particles and particle systems, understanding why most detectors are cylindrical in design versus otherwise, and having a solid grasp of the mathematical foundations of particle detection.
In teaching particle detectors, it is essential to draw connections between the classroom content and real-world applications. Students often ask "what can I use this for?". Even though most of the particle detectors studied in high school are very simple, their general principles of operation are virtually the same as those of large-scale industrial detectors such as those operating at CERN. Students struggle to come up with simple ways to recall particle names beyond the atomic model. This aspect is crucial for mapping each particle with its corresponding track in the detector. It is essential to emphasize that the shape of a detector has a crucial role in its function, eg. cylindrical detectors with collisions at their center are designed this way to maximize output signal. Finally, students can struggle with the relationship between the mass (energy) of a particle and radius of curvature, the charge of a particle, and its direction of deflection in an electric or magnetic field.

2) Best practice example

To grasp the topic of Particle Detectors, students should at least have a good content knowledge on the names of the particles and their basic properties. In that way, when any particle-tracking experiment is carried out, students are able to relate the properties of the particles with how their tracks behave, particularly in the magnetic field. The cloud and bubble chambers are some examples of activities that can be done with the students in order to track the particles that are present around us. However, determining which track belongs to the particles can be challenging to the students. For that reason, it is crucial to have an extension to this activity so students' observation and knowledge can be reinforced. The CCSnap! Card Game (see resources for the game rules and the cards template) challenges students memory and content knowledge; in which students will be able to practise their critical thinking and their attention to detail. The objective of this game is for students to be able to determine the tracks of the particles. Depending on the level of the students, these cards can have slight variations as to how the game is played. Teachers can choose to have this game prior to the cloud chamber activity, which will make the students more aware of what they are supposed to observe, or at the end; when this game acts as a reinforcement of their observation.

4) Helpful material and resources

With these materials we are trying to give solutions to the most common challenges students have in this subject. It is divided into two main groups: those which can be useful for the students themselves and those which can be tools for the teachers to help them and even to make the lessons superfun!
For students:

A manual on how to build a cloud chamber and also to learn about the tracks of the particles.
Taking a closer look at LHC - Detectors. A website about all the information you need to know about all the detectors of LHC in detail.
A game about the standard model : Agent Higgs is looking for some tracks and particles.
A very funny video to understand the accuracy of the data 5 σ
CREDO App - How to turn smartphones into an array of cosmic ray detectors
Ice Cube detector - Science in the news- Perimeter institute
Perimeter Institute resource to introduce students to collaborative way of working in science & key particle terms for detectors.
Perimeter Institute resource to teach conservation of energy and the motion of charged particles in magnetic fields are applied as students examine how particle detectors work.
Perimeter Institute resource where students use data to determine the mass of the Higgs boson and meet other type of detectors like the SNO detector; heavy water used to detect neutrinos.

For teachers:
A very easy idea to introduce the right hand rule
An article about where we can find detectors in our daily life
Games about detectors and standard model such as a particle twister or how to build your own detector. It can be used for any age

Theoretical Physics & Higgs Physics

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1) Key ideas

Modern physics is often hard to understand for students, largely due to their abstract nature. In order to promote theoretical physics and Higgs physics it is good to introduce some of the key ideas across the curriculum. The development of theory, and the experiments used to confirm ideas are important in terms of scientific thinking, which all students should learn. Students are introduced to a very basic model of matter at school, and we could be introducing elements of the standard model including the Higgs boson to emphasize the limitations and excitement in the field.

2) Best practice example

The idea is to run a Higgs day/morning - to promote particle physics and modern physics discoveries. This is in part due to the lack of direct curriculum links. This would be designed for the younger students in a school to capture their imagination and inspire them to study further. Some of this could be done over a series of the lessons or as a whole school. We came up with the idea of trying to replicate the discovery process in terms of data analysis. Firstly by getting a half life curve using the experiment such as here:
Determination of the half life of a model radioactive source e g using cubes or dice
Then re-do this demonstration - and after the 4th roll, provide the students with another 10 dice, then after a further 2 rolls remove 10. The idea being that when they plot their graphs there should be a distinct difference -ideally a bump, a discussion can then be had about how we can recognise differences in data and what it may point to.

3) Helpful material and resources

Reference any material that you find useful for your students and/or your colleagues:

Rolling in the Higgs (Adele Parody) | A Capella Science:	Rolling in the Higgs (Adele Parody) | A Capella Science
Quiz and poster - after the quiz take a sticker (Stickers | The Particle Zoo) of your particle and put it on the poster	Particle Quiz
Quark Puzzle	2D The Quark Puzzle: A Novel Approach to Visualizing the Color Symmetries of Quarks 3D Quark Puzzle | S'Cool LAB
Particle Physics Board Game	Particle Builder (Particle Physics Boardgame) | Zenodo
Oscillations of neutrinos	How do neutrino oscillations work? | Even Bananas 10
Bubble Chamber	Bubble Chamber Pictures for the Classroom | S'Cool LAB
Fermilab	Particle physics at home
Fermilab playlists	Fermilab - YouTube Fermilab Featured Videos - YouTube Lecture Series - YouTube
The animation of signal accumulation in the Higgs boson decaying to two-photon channel	The animation of signal accumulation in the Higgs boson decaying to four leptons channel
	The Standard Model | CERN
	The Standard Model – The Physics Hypertextbook
The analogy of Higgs field and Higgs particle	The Higgs Field, explained - Don Lincoln

Computing in Particle Physics

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1) Key ideas

All sciences are practical by nature and this should be reflected in our teaching & assessment methods, particularly for implementing authentic learning activities. Computing forms a large part of the multidisciplinary field of particle physics, especially when we consider the complexities of the CERN facility. There are three categories of key ideas that we believe could be brought into a high school classroom: Beam control, detector filtering and data processing.

A visit to CERN's control centre illustrates the vastness of the computing power required to create and control the beams needed for cutting-edge experiments. Unlike linear accelerators, beam injection and acceleration in a synchrotron requires precise and coordinated control of several systems across multiple pathways. For example, gradual increase in beam energy requires synchronous adjustment of the accelerators and bending magnets. This demands constant monitoring of the beamline at all locations, forming part of a fast-acting feedback loop. This combination of input and output relates strongly to computing curriculum, particularly as these systems become more autonomous.

Event detection and triggering at each collision point poses significant present and future problems at CERN. Tuning of the detectors' trigger and selection mechanisms is informed by the result of Monte Carlo simulations which continue to require refinement in order to ensure the captured events are of the highest quality and relevance. Additionally, real-time filtering 40 million events per second down to a final 100 events per second for processing requires extravagant hardware and software. For example, the L1 filtering with electronics presents an excellent link to the topics of logic gates. Furthermore, CERN's gradual adoption of Field Programmable Gate Arrays (FPGAs) gives the topic of logic circuits an authentic context for students to work on these devices at a high-school level.

Finally, data processing and storage is an excellent example of cutting-edge computing. Students are often introduced to Moore's Law (doubling of computing capacity every couple of years) in high school. The development of CERN's computing facilities, including the conception of the World Wide Web would provide a conceptual history of the topic in addition to posing future challenges in data bandwidth and storage. Processing of data using the Worldwide LHC Computing Grid (WLCG) also represents an excellent opportunity to distributed computing power, and, in addition to the gradual application of Machine Learning / Artificial Intelligence, shows a clear pathway for students who are looking for genuine applications of advancements in software design.

2) Best practice example

Try to get students' conceptions out in the open first. Let them get a feel for the amount of data being produced. This is a simple calculation that they can do.
For example – tell them a general purpose detector has about 100 million channels and ask them to calculate how many bits they would need to write 100 million (2^… = 100,000,000). So, with 500 particles per collision, and every particle hitting on average 15 channels, how much bits does this use? Now this happens 40 million times per second! How many Mbps is that? (compare to internet speeds, 200 Mbps)

Then go on to how much data would need to be stored in a year when only 100 out of 40 million collisions is saved. (8 bits = 1 byte, 300 days of operation, 4 detectors) Compare to consumer hard drives (5 Tb). And then finally, let them know this needs to be multiplied by a factor 100-1000 for all data, incl. analysis.

Ask them how they would deal with the large speeds and storage space needed. They might even think of a distributed computing grid!
Then go on and ask them what they would think the qualities are that you'd need to work in computing at CERN. Stress that it's all collaboration and teamwork: they will feel less intimidated by the prospect. You also want to engage the students with lesser grades but high motivation, right?
Finally, point out that lots of practical innovations have come out of CERN (WWW, touch screen, medical applications). This might convince a final group of students that working at CERN is actually very useful.

3) Helpful material and resources

1. https://neutrino-classroom.org/TeachersGuideJuly2015/NeutrinoClassroomTeachersGuide-EditedJuly2015.pdf
2. https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LIN
3. https://scoollab.web.cern.ch/sites/default/files/Particle_v2/index.html
4. http://opendata.cern.ch
5. https://opendata-education.github.io/en/

Neutrinos

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1) Key ideas

Showcase the most important aspects of the topic that you consider key for meaningful classroom instruction.

The neutrino was proposed in 1930 by Wolfgang Pauli to keep the conservation of momentum and energy (and spin if you go that far) during β-decay. This is another instance in science when a convenient (particle, planetary mass, black hole, etc) proves to be a real entity. Clyde Cowan and Frederick Reines found experimental evidence of the particle in 1956. This indicates the importance of theory to help predict the existence of certain objects as well as the importance of experimentation to check theory.

Neutrinos initially were thought to have zero mass. Experimental results indicate that there should be some mass (upper limit of 0.09 eV vs. 511000 eV mass for an electron). We believe that neutrinos are also elementary point particles. They have no length or volume and are not made up of combinations of particles. This continues the idea of the relationship between theory and experiments as well as dealing with information.

Because Neutrinos were thought to be massless they needed to move at the speed of light. Now we believe that they have mass they move at slightly less than the speed of light, although our current detectors are not able to find a difference between their actual speed and the speed of light. With experimental error included, it can look as if neutrinos move faster than the speed of light. We don't believe they are. This highlights information about the neutrino as well as the changing nature of science theory as well as making some connections between speed and mass.

Since the standard model shows three generations of fermions, the symmetry of three types of neutrinos seemed likely. This belief was followed by the discovery of the muon neutrino in 1962 and the tau neutrino in 1975. This is another case of the beauty of the theory leading us to discoveries. It also shows a line into the Standard Model.

Abouts 65 millions neutrinos pass through your thumb every second. .Students will ask questions like:

Are neutrinos harmful to the body?
Do neutrinos have mass?
How do they interact?
What is a "ghostparticle"?
Are they invisible or do they have colors?
Do neutrons have flavors?

Neutrons and neutrinos will probably be conflated. To reduce misconception, you can use variation theory. Basically you compare differences and similarities between neutrinos and neutrons.

2) Best practice example

Best Practice Example

High School Students

Sessions	:	4	Class organisation	:	teams of 4 to 5 students
					Each team chooses a particule
Time necessary	:	4 x 1,5h	Output	:	1 poster for each team

The teacher provides :

- The names of different particles: neutrino, quark, electron, photon, muon, gluon, Higgs' boson ...
- A list of questions the poster will have to address
- different ressources, articles, videos, ...etc ... covering :
  - the history of the discovery,
  - The names of the main scientists associated with the particle,
  - the principle of experiences undergone,
  - The keys datas and properties
- At least one question will not be addressed by the ressources and requires personal researches.

Best Practice Example

Junior High School Students

Sessions	:	2	Class organisation	:	Scavenger hunt for teams of 4 to 5 students
Time necessary	:	1 x 1,5h	Output	:	1 quiz for each team listing
		1 x 1,5h			1 question about each of the 10 particules

Session 1

- The teacher spreads out 10 small articles (with pictures and schematics) in a geographically limited area.
- Each article will cover one particle: neutrino, quark, electron, photon, muon, gluon, Higgs' boson ...
- The teacher provides a quiz that will ask a different question for each particle: Name of the discoverer, principle of one experiment, properties (mass, charge, interactions, life duration, ...), ...

Session 2

- All 10 articles are given to all teams. After a group work (including personal researches is needed) each team gives a 3 minutes presentation explaining to the class which particle they find the most interesting and why.

Best Practice Example

Kinder garden

Sessions	:	2	Class organisation :	Session 1 : draw your disguise as a particule Session 2 : listen to other's mouvement
Time necessary	:	30 min 2 x 5 min	Output :	Creativity, and space organisation

Session 1

- Children are asked to choose the name of a particule (neutrino, quark, electron, photon, muon, gluon, Higgs' boson ...) and draw on a mask shaped paper, the name, charge, mass, and decorate it as he/she likes.

Session 2

- Children put on the mask, in semi darkness, children will evolve in the dark and listen to others' mouvements to try and avoid collisions.

Summarise your findings through a brief outline of an instructional strategy. Explain how to best introduce the topic in your classroom. (Body text, Arial 10pt, justified
(leave two 10pt blank lines here)

3) Helpful material and resources

Here are a list of helpful Materials and Resources about neutrinos and neutrino physics geared toward helping teachers integrate neutrino physics into their classrooms. Most of these resources are in English but many are in other languages. Included in the list is a spreadsheet indicating in which languages each resource is available. Also included in this spreadsheet is the link to google translate. Google translate supports 133 different world languages and while not always 100% accurate, does a decent job*.

*It should be noted that google translate does not know idioms or colloquialisms and does not distinguish well between dialects.

Resource Type	Source	Link
Google Translate for Websites: https://translate.google.com/ (Choose "Websites" option at the top)		
Article	FermiLab/ US Department of Energy	https://neutrino-classroom.org/external_docs/neutrino_60-seconds.pdf
Comic Strip	ICE Cube	https://icecube.wisc.edu/outreach/activities/rosie-gibbs/
Article	European journal for school sciences	https://www.scienceinschool.org/article/2011/neutrinos/
YouTube Video	FermiLab	https://www.youtube.com/watch?v=RGv-pcKRf6Q
Article	Frontiers for Young Minds	https://kids.frontiersin.org/articles/10.3389/frym.2020.00045
Article with Handout	Cosmos for Schools	http://cosmosforschools.com/PDFs/Lesson_011_handout.pdf
YouTube Video	FermiLab	https://www.youtube.com/watch?v=J8dRZjOD_ME
Collection of Activities	Neutrino Classroom	https://neutrino-classroom.org/TeachersGuideJuly2015/ NeutrinoClassroomTeachersGuide-EditedJuly2015.pdf#page70
Collection of Articles and Activities	Fermilab	https://neutrinos.fnal.gov/
Collection of Posters and Videos	SNOLAB	https://www.snolab.ca/outreach/resources-for-students-educators/
Articles	Gran Sasso National Lab	https://www.lngs.infn.it/en/educational
Article	Smithsonian	https://www.smithsonianmag.com/science-nature/looking-for-neutrinos-natures-ghost-particles-64200742/

Antimatter Research

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1) Key ideas

The ideas of antimatter have been around for decades, starting with Dirac’s equations in the 1920’s which predicted antimatter existed. Shortly after, Carl Anderson detected a positron in a cloud chamber, proving the existence of antimatter. Both of these scientists earned a Nobel prize for their work.

The behavior of matter and subsequently antimatter are the biggest concepts that students need to understand. Annihilation in particular, is a big topic but can be very difficult since we cannot see it with our own eyes in the classroom. It is important for students to know that matter and antimatter annihilation occurs, how it works and how it relates to pair production. Hawking radiation and beta decay are two phenomena where we know antimatter plays a significant role in the universe and are great practical examples for students. The concept of potential wells is important for understanding the way we handle antimatter. This can be discussed in relation to gravity and potential energy, a subject which commonly introduces the idea of a potential well.

When it comes to student’s questions on the topic, teachers should be aware that saying “we don’t know” is going to happen a lot. Language should be considered strongly as you try to explain key ideas. The words you use (such as *model*) can really help in development of ideas around antimatter.

2) Best practice example

The idea of annihilation can be a challenge, particularly in the classroom as we cannot see it with our eyes. We can use other ideas to give a frame of reference since we cannot show annihilation in our classrooms. The following are some of these ideas and concepts that could be used to model annihilation for our students. For example, opposite numbers, forces with action/reaction, viruses and an antidote, neutralization reactions, the law of conservation, and noise canceling headphones. Here are more details about how some of these ideas can work.

In mathematics, the quadratic equation $x^2 = 1$ has roots $x = \pm 1$. The sum of those roots is 0. So, in a way, they “annihilate” or cancel each other out.

In chemistry, every chemical compound exists on a pH scale (from 0 to 14). 0 is very acidic, 7 is neutral and 14 is very basic. If we have an acidic compound at pH 5 and add an equal amount (in moles) of a basic compound at pH 9 we would end up with a neutral mixture at pH 7. This is a very practical analogy which is available for students to experience, in real time, in the chemistry lab.

In noise canceling headphones we can use the idea of superposition with waves. In class you can have two waves drawn on a transparency or acetate so that they can be overlapped. Have students use the information to show the superposition of the two waves (functions should cancel out). This will have students see a sample where a crest and a trough cancel each other out, much like is done in noise canceling headphones.

While the word “antimatter” may not exist in your curriculum, there are many areas where you can find it. Examples include: Black holes, Hawking radiation, PET scans, the Big Bang Theory (matter-antimatter asymmetry), Beta decay, Supersymmetry Theory, and when discussing the standard model. A few ideas for how to cover this with your students include acting out reactions, unit conversion calculations, and storage of the antimatter.

Having students act out reactions is a great way to get them moving and thinking about particle physics. If each student is given “a particle identity”, electron or positron, and then set free to walk around the room, they would then need to interact with their classmates according to their given identity. When an electron and positron meet, then they would need to annihilate by running away quickly because they are now photons moving at the speed of light! You should have 1-2 more electrons than positrons to point out the matter-antimatter asymmetry. This “Big Bang simulation” becomes even more exciting, if the simulation starts in a dark classroom (or preferably gymnasium to avoid damage) and each one has a flashlight that is lit when a particle becomes a photon!

Unit conversions are another place where antimatter can fit into a lesson nicely as a way for students to get the mathematical practice while calculating with data from a different source. This is also a way that you could bring antimatter into a classroom with younger students. Have the students begin with a particular amount of antimatter and then calculate how much energy it would produce and end with how long it would take to produce that amount of antimatter.

Storage of antimatter once it is produced is a great way to discuss magnetic and electric fields. After antimatter has been created a magnetic field is used to center the antimatter so that it does not interact with the walls around it. Then charged plates are introduced on each end to keep the antimatter trapped. The antimatter then bounces from plate to plate remaining within the walls of the container. This is a great application of magnetic and electric fields that students can use to understand how we store antimatter, even if it is only for a short period of time.

3) Helpful material and resources

Antimatter Research Lecture by Sameed Muhammed (HST 2022, CERN): indico.cern.ch/event/932906/contributions/4890303/attachments/2479886/4256862/20220713_What's%20the%20Matter%20with%20Antimatter.pdf
Antimatter Factory at CERN 360°: alpha.web.cern.ch/sites/default/files/360-tours/CERN-AD/HD/index.html
Hands on antihydrogen simulation CERN:massen.web.cern.ch/hoat/
Antimatter: home.cern/science/physics/antimatter
Antimatter Matters Lesson: www.teachengineering.org/lessons/view/uoh_antimatter_lesson
Virtual PET Workshop: https://virtual-workshops.web.cern.ch/pet-virtual-workshop/
Antimatter in the classroom: cds.cern.ch/journal/CERNBulletin/2010/12/News%20Articles/1248913
Antimatter sonata LHCb: home.cern/news/news/experiments/sonata-lhcb-sound-antimatter
Angels and Demons and antimatter Q&A: web.archive.org/web/20070310025718/http://public.web.cern.ch/Public/Content/Chapters/Spotlight/SpotlightAandD-en.html
Would and Antiapple fall up?: www.newscientist.com/article/dn14120-would-an-antimatter-apple-fall-up/
Perimeter Institute Lessons on Black Holes or the Big Bang: resources.perimeterinstitute.ca/collections/astrophysics-cosmology

Video Links
Antimatter Explained: www.youtube.com/watch?v=Lo8NmoDL9T8
Antimatter Rap: www.qedfoundation.org/the-antimatter-science-rap/
TED Talk What Happened to Antimatter: ed.ted.com/lessons/what-happened-to-antimatter-rolf-landua

Future Accelerators

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1) Key ideas

As Physics teachers coming from 5 different countries (Ireland, India, Thailand, Italy and USA) and drawing from different curricula (IBDP, A-Levels, Advance Placement, Italian), our discussion revealed that some of us teaching Particle Physics at the basic level, while for some, this does not appear at all across our curricula. This means establishing the moral reasons for investigating the topic outside of the curriculum in itself as well as establishing the core knowledge without which, what we teach as well as further development, would be unintelligible.
To draw the interest of students across the 11-18 age range to a topic as complex as the future of particle accelerators, we need to comprehensively understand the history of accelerators as well as the questions which have animated scientists in their construction.. This will lead to an investigation into which questions are outstanding and why we need even more of them in the future as well as how the current range of colliders can be amended. Additionally, we should discuss some basic and familiar physics concepts underpinning accelerators to help them relate it to existing knowledge.
Some of the key ideas that could be discussed to get the students curious and also reinforce existing physics concepts :

- Evolution of Accelerators: Electrostatic to Oscillating
- Linear accelerators, Cyclotrons, Synchrotrons
- Electric and Magnetic Fields
- Constant and Oscillating Fields
- Lorentz Force
- Relativistic Transformation
- Focusing force: Hooke's law, Harmonic Oscillators
- Dipoles and Quadrupoles
- Superconductors
- Collisions

Future colliders is an advanced sub-topic in an already advanced topic of Particle Physics. So drawing their attention to the famous Large Hadron Collider, Higgs Boson and The Big Bang can trigger interesting discussions in the classroom rooted in scientific work presently being done as well as establishing the fundamentals of what has already been accomplished. Some research time can be allowed to bring forth the high points of LHC's achievement.
A significant part of this lesson is not what is known but what is unknown- and how it might be found which requires a degree of specificity. This involves knowing what colliders have discovered up to now, what colliders currently exist, the technical specifications of them such that they can be improved and adjusted, how adjustment to these factors would have experimental consequences, what experimental consequences would be desirable for inducing new conditions which could break the standard model, the new colliders which have hitherto not been constructed, what the reality of construction would entail.

2) Best practice example

A successful example of a lesson focused on future accelerator projects would explore the construction of colliders,and the variety of colliders which are being constructed presently. This would involve exploring the distinctions between:

- Higgs/Electroweak
- Positron/Electron collisions
- Super Proton-Proton Collider
- Muon Colliders

The next focal point of the lesson would be exploring what these colliders are looking for explicitly- with a focus on broad overviews of antimatter, explanations for dark energy, dark matter, and actively testing and potentially breaking the Standard Model. Other questions we might encounter might include how the Higgs itself acquires mass, and whether leptons are fundamental particles.

The lesson would at this point feature a series of hinge questions to ascertain understanding and security before any more progress was made. Students would then be asked to evaluate which colliders were best aligned with approaching each problem, and to provide an explanation as to why each collider was suited for that specific task.

Having differentiated between these colliders,the lesson would then examine the major changes in technology which would allow significant developments in collider science. The most accessible elements of this which could be used to generate discussion using existing knowledge from the wide array of curricula are the following:

- Superconducting Magnets
- RF Technology
- Improved alignment of targets & sources
- Advanced Acceleration
- Beam Physics Advancements

    - 1. Beam Cooling
    - 2. AI (Optimization of Beam targeting through machine learning)

By the end of the lesson, we've would hope to have educated students as to

1. The Future Colliders currently being examined
2. The problems these colliders are designed to resolve
3. The methods by which these colliders could be improved still further in the future.

Moreover we hope to let them understand that reaching ambitious scientific objectives, like those envisioned by the FC studies, requires the development of advanced instruments, new technologies as well as the training of the next generation of researchers in different fields. We would also stress that investing in large-scale research projects like the FC can bring tremendous benefit to society and the economy.

3) Helpful material and resources

1. Challenges of Future Accelerators for Particle Physics Research
   https://www.frontiersin.org/articles/10.3389/fphy.2022.920520/full

Challenges of Future Accelerators for Particle Physics Research is a paper which was recently published in Frontiers in Physics on 27th June 2022. This paper provides an overview of the present state of accelerators for particle physics and gives a brief description of some of the major facilities that have been proposed, their perceived advantages and some of the remaining challenges.

2. CERN Homepage about the future circular collider
   https://home.cern/science/accelerators/future-circular-collider

This is a CERN homepage which provides the future circular collider study. It gives an overview of a new scientific tool for the post-LHC landscape, a scientific mission for the 21st century, preparing the next-generation of particle colliders to boost the energy and intensity frontiers, designing a sustainable research infrastructure through collaborative R&D, and the FCC conceptual design reports.

3. CERN needs for future accelerators in high energy physics
   https://link.springer.com/content/pdf/10.1140/epjst/e2015-02572-x.pdf

CERN needs for future accelerators in high energy physics is a paper which was published in THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS in 2015. The article gives a number of examples of the studies, the beam parameters that are foreseen in the different projects and their proposed technical layout.

4. Introduction to Particle Accelerators and their Limitations
   https://arxiv.org/pdf/2007.04075.pdf

Introduction to Particle Accelerators and their Limitations is a paper which was published in proceedings of the 2019 CERN–Accelerator–School course on High Gradient Wakefield Accelerators, Sesimbra, (Portugal) in July 2020. The paper gives a short overview of the principles of particle accelerators, their historical development and the typical performance limitations. After an in- troduction to the basic concepts, the main emphasis is to sketch the layout of modern storage rings and their limitations in energy and machine performance. Examples of existing machines - among them clearly the LHC at CERN - demonstrate the basic principles and the technical and physical limits that we face today in the design and operation of these particle colliders. Pushing for ever higher beam energies motivates the design of the future collider studies and beyond that, the development of more efficient acceleration techniques.

5. The physics and technology of the Future Circular Collider
   https://www.nature.com/articles/s42254-019-0048-0

The physics and technology of the Future Circular Collider is a paper which was published in Nature reviews Physics in March 2019. The recently published FCC Design Report documents the different machine parameters, the physics opportunities and the challenges for further strategic research and development. A staged integrated programme is proposed, in which one of the colliders explored by the FCC study, the FCC-ee, could be operational by 2039, just after the end of the HL-LHC programme, which would be followed by an FCC-hh physics programme starting in 2050–2060. Evidently, the success of such an ambitious project depends not only on international scientific collaboration, but also on partnerships with industry and collaborations with many professionals, including many non-STEM (science, technology, engineering and mathematics) fields.

EXTRA MATERIAL

Future applications of the discoveries of colliders yet to be built are obviously unknown right now, so we would stress the scientific virtue of exploration and inquisitive, rational thought in order to achieve a better understanding of the world and the universe. Moreover the importance of developing new, more efficient, devices in order to observe phenomena not observed until now because of technological limitations .
In order to achieve these results several skills are needed, as shown in the picture

And at the moment the matter we know and that makes up all stars and galaxies only accounts for 5% of the content of the universe! Dark matter seems to outweigh visible matter roughly six to one, making up about 27% of the universe.

Concerning future lepton ring colliders (or to be more precise electron-positron colliders) the synchrotron losses set a severe limit to the achievable beam energy. And very soon the size of the machine will be

beyond economical limits: For a constant given synchrotron radiation loss the dimensions of the machine have to grow quadratic with the beam energy.
Linear colliders therefore are the proposed way to go. And in this case the maximum achievable acceleration gradient is the key issue. New acceleration techniques, namely plasma based concepts where gradients are observed that are much higher than the present conventional techniques, are a most promising concept for these future colliders. An impressive example is shown in Fig. 38. Within a plasma cell of only some cm in length, electrons are accelerated to several GeV. The gradients achievable are by orders of magnitude higher than in any conventional machine. Still there are problems to solve, like overall efficiency, beam quality (mainly the energy spread of the beam) and the achievable repetition rate. But we are convinced that it is worth studying this promising field.