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Focus Groups

FINAL REPORTS

CONTENTS

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Particle Physics & Errors and Uncertainty

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Key ideas

Particle Physics is a modern Physics. According to the leading expert, Jonathan R. Ellis (University of London (GB), the aim of Particle Physics is to find an answer to: “What is matter in the Universe made of? Research so far through the application of Large Hydron Colliders (LHC) confirmed the existence of fundamental particles and the particle systems.
Fundamental particles consists of particles that can not be divided further. Fundamental particles include: Bosons, Quarks, Fermions, Leptons. A particle system is one that is made of more than one fundamental particle. Particles system include: Protons, Neutrons, Pions and Kaons. Four Fundamental interactions: Electromagnetic force, Gravity, Weak nuclear force and Strong Nuclear force.
According to the topic ‘Error and Uncertainty’, it is important to consider the difference between experimentalists, theorists and phenomenologist, because all of them need to deal with error and uncertainty problems in different ways. Specifically, experimentalists need to choose which experiment need to use or develop depending of the possibilities and resources. For that reason, the decision needs to be thinking in terms of formal logic and common sense.
Error in a physics context deals with how our inherent biases, and mistakes influence the data collected in an experiment. Students often confuse this concept with uncertainty, which focuses on the limitations of the devices used to collect data.
Similar confusion exists when comparing accuracy and precision. Accuracy refers to how close to a ‘correct’ or true value, while precision looks at how well an experiment is set up to create repeatable measurements of similar events. Ideally, an experiment should have both good accuracy and precision, it is likely better to have less precision if means better accuracy.

Best practice example

To help students understand the ideas of errors and uncertainty, the Rolling with Rutherford activity, provides an opportunity for students to collect data, and examine the idea of uncertainty in a true particle physics context. This activity was developed by Quarknet.
http://www.hep.fsu.edu/~wahl/Quarknet/summer2014/docs/Rutherford.pdf

Students roll marbles down the system and record the number of collision events with targets per number of marbles. After rolling marbles at the target, and collecting the number of collisions, students can create a histogram of their data, in a way similar to work done by particle physicists.

Students can conduct a simple calculation to determine the width of the target in the experiment:
$P = ND/L$
Where: P = the probability of the hit occurring (maximum histogram value/total number of events)
N = the number of targets
D = the diameter of the target
L = the width of the system

One of the nice things about the activity is that you could have students conduct analysis with different amounts of data (e.g. after 10 marbles, after 50 marbles, after 100) to look at how their resulting calculated diameter.

The activity can be further extended by changing the size of the ‘target’, which would bring a more complex calculation, and shows how scientists develop more complex models over time.

Particle Accelerators

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Key ideas

The most important aspects of this topic in a classroom setting are to do with the forces experienced by particles when traveling in an electric or magnetic field. Students must realise that it is the electric field that causes the particles to accelerate. The magnetic field, on the other hand, the bends the trajectories of these particles. Students should be able to calculate the values of these forces in Newtons by substituting the known quantities into these equations:

$$F_E = qE$$
$$F_B = q(v \times B)$$

Because force is a vector quantity, it is important that students establish the direction of these forces. For example, the use of right hand rule will give the direction of the magnetic force on a moving charge. This magnetic force depends on the direction of the magnetic field and the direction in which the particle is travelling. However, in order to do this successfully, students need to understand the polarity of magnets and the implications of reversing this polarity (or reversing the direction of the particle) on the deflection of the particle. Furthermore, the charge of a particle also determines the direction of the induced force, for instance, if a proton curls upwards in a uniform magnetic field then an electron will deflect downwards in the same uniform field.

Students also need to understand the terns 'velocity' and 'acceleration' as these terms clearly relates to particle accelerators. In addition to this, they need to realise that there is a natural speed limit for any particle due to Einstein's special theory of relativity.

Best practice example

Students could design, modify or simply extend an experiment on accelerators (which is the basis for all particle interactions at the Large Hadron Collider) in order to address their own hypothesis or research question. This could mean building or modifying a linear or a salad bowl accelerator and examining the effect of changing a single variable such as the electric potential on the velocity (kinetic energy) of the particles at various points in the accelerator. The use of Vernier data loggers and probes, for instance, will help students gather, record and process the data in a meaningful way in this investigation. Appropriate computer simulations or applets involving particle accelerators could also be used to generate and analyse relevant data.

Particle Detectors

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Key ideas

To be able to understand the contents, the students need the foundations beforehand. Students often have difficulties understanding the right-hand rule for magnetic forces. Even more, students might have a hard time understanding invisibility of particles, since particles can only be seen when they interact with matter.

Students should be able to understand the concept of detecting particles. Furthermore, they should understand the principles and differences between cloud chamber and bubble chamber. The function of particle accelerators and the principles of particle detectors needs to be captured. They have to understand the principle of particle disclosure in the detectors, for instance, in the silicon detectors.

As a foundation for the points from above the students need to have an overview of electromagnetic fields as well as what a particle is. In addition, the fundamentals of invisibility and their structure have to be known by students. Also, the trajectories of particles and the deposition of energy, and how momenta of particles and the energy is measured.

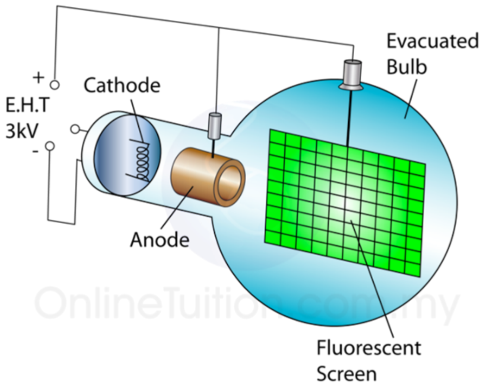
Conceptions and challenges for the students are given to recognize, that particles can only be seen when they interact with matter. They might think that only 1 proton against 1 proton is being collided in LHC. Students need to understand that particles by collision don't decay, but secondary particles are formed. One might have difficulty and frustration to use data containing momenta and energy values.

Best practice example

Here below we describe a possible progressive didactic sequence of three activities to introduce students to particle detection by visualization of the particle track and to measure a property of the particle using the track.

Activity 1 - Cloud chamber: Cloud chamber are impressive as they allow students to visualize particle traces with their naked eyes, mostly electrons from cosmic ray showers and alpha “particle systems” from the radioactive emission of radon present in the air. In addition, the physics teacher can connect with the chemistry teacher to help students understand that the alcohol vapour is *at the limit of phase transition*, namely at the limit of condensation. Hence, when a particle passes through the medium it will trigger condensation of alcohol droplets along its track, thus making the track (and *not the particle*) visible. A daily example of this phenomenon is the cloudy traces an airplane leaves behind when the atmosphere is saturated in water vapour.
In case you cannot find the material to build a cloud chamber with students, we recommend showing them a youtube video, e.g., https://www.youtube.com/watch?v=e3fi6uyyrEs

Activity 2 – Cathode ray tube: Here we propose to use cathode ray tube (CRT) that contain a fluorescent screen inside the vacuum bulb. Firstly, to emphasize again how we can visualize particles and secondly, how we can measure the momentum of the particles (here electrons).
In a first step, we can ask students if they can see the electron beam going out of the cathode. Why not? What do they see in the screen then? As in the Activity 1, we want to reinforce the idea that particles can only be seen through their interactions with a medium.



(a)

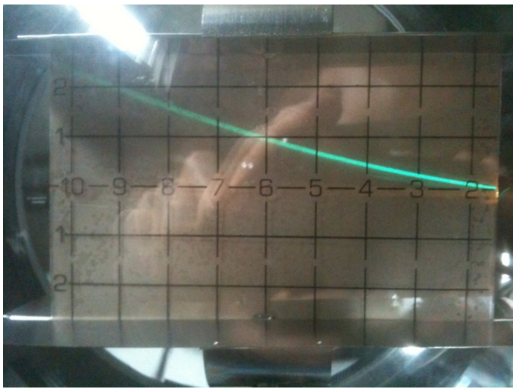

(b)

FIG.1 (a) Schematics of the CRT. (b) Photograph of the fluorescent screens where markings are in cm. The greenish circular track is caused by the impact of the electron beam onto the screen causing fluorescent emission. The trace is circular because a magnetic field is applied.

In a second step, students should figure out how to measure the momentum of the electrons by applying a quasi-uniform magnetic field produced by two coils on each side of the CRT (see Fig. 2). They should find out that using Newton's 2nd law with a centripetal acceleration allows them to derive a simple relationship between the radius r of the trajectory and the magnitude of the momentum p. The second law in magnitude here reads:

$$a = \frac{v^2}{r} = \frac{e v B}{m} \Rightarrow p = eBr$$

To determine p, they only need to find the radius r by measuring the x-y coordinates of one point of the trajectory (and using Pythagoras' theorem). For B, they should be given the equation of Helmholtz coil and measure the current intensity.

Activity 3 – Momentum in modern detectors: Here we chose to focus more specifically on the tracker chamber of modern detectors like ATLAS in the LHC (although in the case of muons momentum is also measured in the muon chamber). For this we can use the online HYPATIA simulation of the ATLAS detector here: https://hypatia-app.iasa.gr/Hypatia_Vaadin-1.0/?lang=en&layout=medium
This simulation can be used to briefly explain the different layers of the detector. The momentum here is measured in the inner part of the detector called the "tracker", an immense cylinder of Silicium pixel detector surrounded by a huge solenoid producing a quasi-uniform magnetic field (perpendicular to the front view in FIG.3). Particle tracks bend slightly in the tracker, although we cannot see the curvature of the tracks in the simulation.

Now that students know how the momentum is measured, they can carry out an activity with the momentum values of the tracks. We propose the activity "Conservation of momentum in particle collisions" from the Go-Lab repository: https://www.golabz.eu/ils/conservation-of-momentum-in-particle-colisions.
In this activity, students will analyze simple events producing muons and compute the total momentum in transverse plane. A surprise awaits at the end, as they will realize that momentum is never conserved, as the missing momentum is attributed to escaping neutrinos.

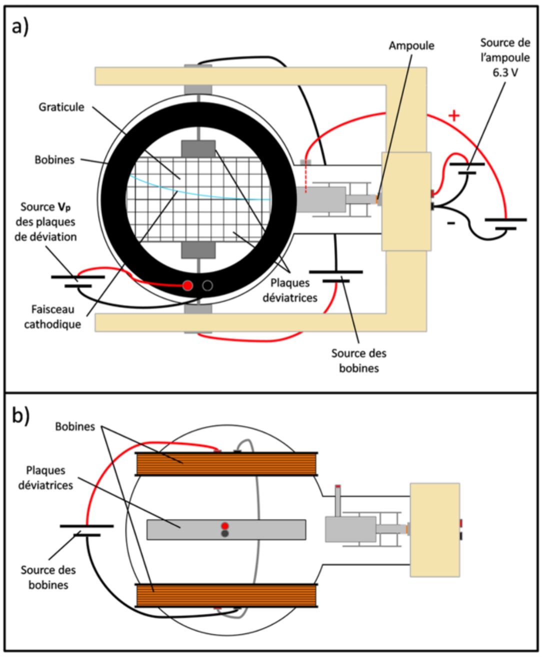


FIG. 2 (a) Deflection of the electron beam by a quasi-uniform magnetic field produced by two coils on each side of the CRT. The $\overrightarrow{B}$ vector points inside the page (b) Top view of the setup

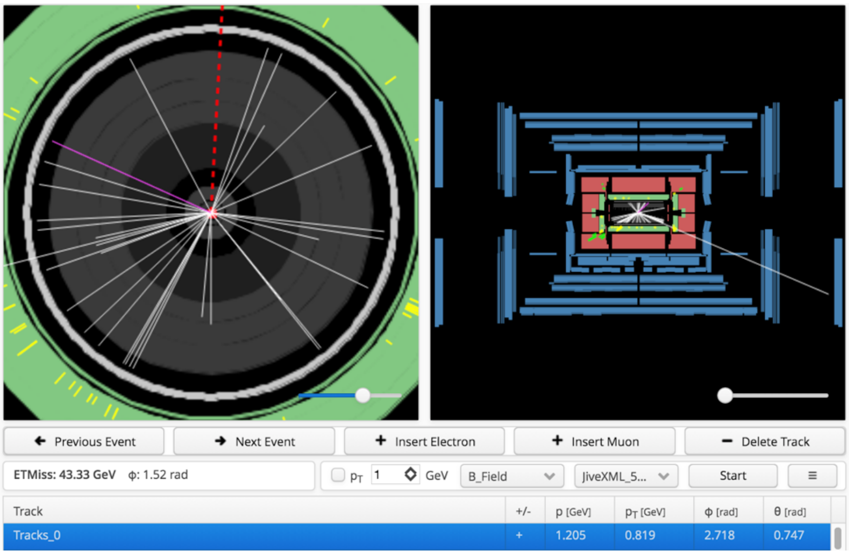


FIG. 3: Screenshot of the HYPATIA online ATLAS simulator. (left) Zoom front view of the tracker. The tracker is surrounded by a cylindrical solenoid which is the grey circle inner of the green layer, which is the electromagnetic calorimeter (right) side view.

Data Analysis in Particle Physics

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Key Ideas

There are a number of Key Ideas we have identified in the Data Analysis section. Overall, students should understand the many lenses that can be used to view data and that the choice of lens can determine what the data will reveal. Much of data analysis is learning to separate the chaff from the wheat or the interesting data from the background noise. It is also important for students to understand that models are developed that provide predictions that experimental results are compared with. There are several "Dark Matter" key concepts that, like dark matter, we know exist but are difficult to explain. These include converting physical data to mathematical data and then to mathematical models. These can be quite complicated in the case of particle physics.

Best Practice Ideas

To teach these key ideas we developed an analogy involving the detection of "cheating" in gambling which will be used to describe the discovery of the Higgs particle. To start the game, students will be divided into 5 groups (particle bunches 😀). All of the groups will roll 4 dice 100 times and record the sums of the dice for each roll. This data will be graphed as a histogram with number of events on the vertical axis. All groups will then repeat this except instead of simply summing the faces of the die, they will apply a provided rule to the summation. For example, "If the sum is <7, then add 100 and divide by 2." They will also be encouraged to do it a third time with a rule they devise. All groups will then display and discuss their histograms.
We expect to see a Gaussian curve on the "normal" rolls, but a non-Gaussian curve on the "rule" based rolls. Students will see that adding a rule distorts the expected distribution. Students will then be shown a slide of the Higgs data as it is collected. With small amounts of data, it will not be clear that there is a deviation from the expected curve. Only by increasing the amount of data can the deviation be seen clearly.
In this analogy, the rolling of the dice is a collision. The rule applied to the dice represent a possible result of the collision. The result of the rule is some measurable physical quantity like invariant mass or total energy. Each rule will result in a different probability distribution.
"Normal" rolls represent a basic model, and rolls with "rule"-based rolls represent some extensions of the basic model (with some additional particles or interactions added). In this way the Higgs particle distribution clearly shows a rule being applied to the expected outcome.

Computing at CERN

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Key ideas

Our students need to be provided an initial concept of what computing is. Why do we need it?
The size of data has grown significantly over the lifetime of computing science. Computing capacity has evolved over time; compare the Apollo 11 launch with current cell phones for helpful illustration.
We will seek to answer the question: What physics experiments are generating such a large amount of data? As well as: What do we need computers to be able to do in an effort to process such a large quantity of data? We do not currently possess the computing power necessary to execute cutting edge scientific research which has already been theorized.
A common concern with large data sets is what to do with them once they have been collected. Storage and large scale data analysis (computing capability) are limits which have been overcome at CERN using a global computing grid (WLCG) to share computing power and storage capacity.
Data needs to be preserved for future generations so that it meets the FAIR criteria (data must be Findable Accessible Interpretable Reusable). The fiscal investment in current data and evolution of understanding moving forward provide reasons of importance in this system of preservation.
Using open access data from the CMS detector at CERN, we plan to show our students the power of computing within the classroom.

Best practice example

Using open access data from the CMS detector at CERN, we plan to show our students the power of computing within the classroom. We will use the lesson plan found at QuarkNet
The classroom lesson will follow the following structure:
1.After an introductory explanation to computing, students are put in small groups of two or three and begin the activity by accessing the CMS MasterClass.
2.Student pairs then open different files of real data from the CMS detector by clicking the icon at the top left of the screen, and clicking 'Open files from the Web'. Each pair of students should open a unique data file.
3.Once the file is uploaded, students will be able to rotate, zoom, and otherwise manipulate the images of the collisions.
4.Students will use a cheat sheet (found here) to analyze data to classify ~100 individual events within their data sets.
5.Once all events have been identified, students will enter data into a class-wide spreadsheet.
6.The spreadsheet will be used to generate a class wide histogram for all data sets analyzed.
7.Using the histogram, students can extrapolate particle masses. (Include money denomination metaphor.)

Medical Applications of Particle Physics

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Key ideas

- Particle Physics is not only a fundamental kind of science but also delivers important medical applications.
- There are two main aspects about medical applications: medical imaging and medical treatment.
- These applications are still being worked on, e.g. proton therapy.
- Besides using particles, medical imaging can also be done using ultrasonography and nuclear resonance (MRI).
- Most commonly used techniques for medical imaging are ultrasonography, X-ray and CT scanning, PET and gamma scanning, MRI.
- For treating cancer, tumors are killed with X-rays that harm healthy tissue. Therefore, new techniques are being developed like proton therapy. We need accelerating techniques for that, and these were developed at CERN.
- Modern medical scanners rely heavily on the strong, uniform magnetic fields, produced by devices that utilize superconductors.
- The acceleration of charged particles in particle accelerators and in many medical imaging devices depends on the presence of electric fields.
- Imaging has enabled medical practitioners to improve diagnosis with fewer invasive procedures.

Best practice examples

1.Arrange a visit to a local hospital to find out more about imaging

2.Group Work

Assign different groups different medical instruments to investigate and share their knowledge with the class. *"The aims of modern education and of inquiry-based education in particular require students to become more independent learners. This means teachers developing new relationships with students and having the confidence to allow students to develop their own ideas."*[12]

1.Jigsaw

- Divide the topic "Medical instruments and Particle Physics" into a few constitutive parts ("puzzle pieces").
- Form subgroups of 3-5 and assign each subgroup a different "piece" of the topic (a different instrument).
- Each group's task is to develop expertise on its particular subtopic by brainstorming, developing ideas, and if time permits, researching.
- Once students have become experts on a particular subtopic, shuffle the groups so that the members of each new group have a different area of expertise. Students then take turns sharing their expertise with the other group members, thereby creating a completed "puzzle" of knowledge about the main topic (see Silberman, 1996). A convenient way to assign different areas of expertise is to distribute handouts of different colours (or labelled with different words/letters). For the first stage of the group work, groups are composed of students with the same colour of handout; for the second stage, each member of the newly formed groups must have a different colour of handout.

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The Higgs Boson

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Key ideas

- Mathematical model predicted the particle before it was experimentally discovered
- Standard model and the Higgs boson
- In particle physics there is a probability that something happens, so we have to collect a lot of events.
- Data analysis / statistics

Best practice example:

While we study the black body problem, we show how the Rayleigh model didn't fit with the experimental observations so physicists began to look for another model. Max Planck, in an effort to solve this problem decided to create a mathematical model of the experimental results and he came out with an equation which showed that energy was quantized (even if he couldn't believe it). A few years later, Einstein used the Planck constant to explain the photoelectric effect introducing the concept of photons.

The Higgs discovery happened in a similar way. There was an issue in the Standard Model that required all elementary particles to be massless, which was impossible. So, Peter Higgs (and others) created a new mathematical model that required the existence of the Higgs boson At the time, we didn't have the technology to prove its existence. We only discovered it 40 years later.

The similarity between the development of the theories of Planck and Higgs would allow a teacher to introduce the Higgs Boson in his/her classroom without adding a significant amount of time to their already time constrained curriculum.

An opportunity for students to "see" the Higgs Boson and to learn more about how it was discovered at CERN is called the CMS or ATLAS Masterclass. This one day field trip event is sponsored by IPPOG (in Europe) and QuarkNet (in the USA) and involves having the students attend a local university and to be a particle physicist for a day. Students will experience lectures and tours at the university in the morning. In the afternoon the students will analyze events using an event display. The results of their analyses will be presented in a histogram. The final event of the day will have the students participate in a videoconference with students in other parts of the world to discuss the results of the day.

Antimatter Research

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Key Ideas

We organized our key ideas into four main categories, “What is antimatter?”, “How is antimatter produced?”, and “What is it used for?”. In order for students to answer the first question, they need to learn the first about particles and antiparticles and the properties of each. After learning about particles and antiparticles, they can build antimatter particle systems and predict properties.
The next question, “How is antimatter produced?” is important because we would like students to understand that antimatter can be produced in natural processes such as radioactive decay (positron emission) as well as produced in a laboratory. The simplest atomic version of antimatter, antihydrogen is produced at the CERN antimatter factory. Describing the production and containment of antihydrogen provides a chance to discuss some important concepts of antimatter. For example, only a particle and its antiparticle can annihilate and this process may not be instantaneous.
In teaching about antimatter and its interaction with matter, conservation laws are an important key idea. Studying antimatter/matter interactions can be used to show students how to apply conservation laws. For more advanced students, Feynman diagrams can be introduced and used to describe particle interactions and transformations. It is important to take time when introducing Feynman diagrams because they can easily be misinterpreted by students. Antimatter/matter interactions are also a good way to introduce the concept of energy and matter equivalence ($E \leftrightarrow mc^2$).
It helps some students to relate better to a concept when they learn about applications. Discussing PET scanners and cancer treatment also allows for opportunities to teach concepts related to antimatter. For example, when studying PET scanners you can discuss annihilation and conservation laws (the production of two photons in the process). It also shows students how basic research can be important for developing technology that is important for society. For students with different interests, it is good to discuss medical applications as well as other types of applications if possible.
Including examples of antimatter research in curriculum provides opportunities to discuss some of the unanswered questions we currently have in physics, like why were matter and antimatter produced in slightly different amounts in the early universe, what is dark matter and how are we trying to figure out what it is, and will matter and antimatter behave the same in a gravitational field.

Sample Lesson

The lesson described in this paper is part of a larger course on particle physics taught four times to German students (ca. 200 students in total) age 15-16. The whole course is approx. 10 x 90 minutes long, the antimatter section is approx. 2.5 x 90 minutes. The course is made more popular by avoiding formal mathematical description, only basic arithmetic is used and I tell the students at the very beginning

Since the antimatter part of the course starts after the standard model was introduced, the students are already familiar with the concept of matter and force particles, the description of the particles with their respective charges, the creation and stability of particle systems and transformation between particles. Students have been introduced (again) to the central role of conservation laws and built or used a DIY cloud chamber.

Lesson 1 Introduction to Antimatter and motivation for the students

As long as the movie "Angels and demons" is still popular, a segment from this movie is the obvious choice to discuss the more exotic subject of antimatter.

Let the students watch (at least twice) a short section of the movie (where the helicopter crashes and the battery of the container gets low). Let them describe their observations and record those observations.

Typical observations can be:

- huge amount of energy is released
- something (with a battery) kept the explosion from happening.
- A bright flash appears

Build on those observations and show an image of a positron-electron annihilation (from the bubble chamber). Make clear, that this is the elementary process.

At this point there are (at least) two choices, let the students "construct" the antiparticles that correspond to the already known particles (quarks are most difficult, electrons are the easiest). This gives the students something easy to hold onto. The other choice is to let the students analyze the actual image and derive the physical properties. To do this, students must be familiar with the quantitative analysis of tracks[1]

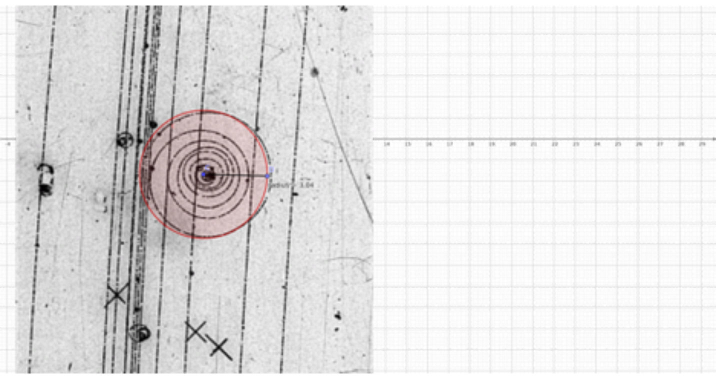
In either case, students learn the principle of antimatter particles as mirror particles and the fact that they have mostly identical properties, in particular when it comes to observation of chemical properties.

The most important part of the first session is now the analysis of the "reaction equation" ($e^+ + e^- \rightarrow 2\gamma$). The form of such an equation is known from chemistry. Discuss the most important equivalence of mass and energy and make clear that the "=" sign in $E=mc^2$ has a different and deeper meaning than the same sign in mathematics.

The final activity of the first session is "Build an Anti-Hydrogen Atom".

Materials:

- CERN bubble chamber website for bubble chamber images: https://hst-archive.web.cern.ch/archiv/HST2005/bubble_chambers/BCwebsite/index.htm
- Trailer of "Angels and Demons" - https://www.youtube.com/watch?v=zzjv-GUEDfg (ca. 0:50)
- Cards or 3D symbols for the particles from QuarkNet or Netzwerk Teilchenwelt (available online in german)



Example of an geogebra sheet

[1] You may want to load the bubble-chamber image into the background of a geogebra sheet – students can measure the curvature more easily that way.

The second session.

As a warm up game you may want to distribute cards with particles and antiparticles on it and challenge the students to find the respective mirror particle (if you want to make it harder, leave out the names and provide only the charges and mass).

The rest of the session is dedicated to ongoing research on antimatter. Particular attention is given to a connection with “known” physics in order to give the students a feeling of “it is not SO hard to understand”.

It is usually organized either in the from of a jigsaw puzzle or groups doing the research and presentation in the conventional way.

Possible topics might include:

1. gravity GBAR et al. (connect with Newton mechanics)
2. cooling (connect it with thermodynamics and possibly QM / Laser physics) and
3. Storage (possible connection with magnetism)
4. Spectroscopy (connect with chemistry)
5. Where has the antimatter gone? (Cosmology, precision of measurements)
6. Other current experiments

As the final assignment ask the question:

How can you find out, whether the sun is made of matter or antimatter?

You may want to break this assignment into smaller parts.

What if you have more time or more advanced students?

1.What is antimatter used for in present day applications?
2.Use the creation-annihilation process as an example to introduce Feynman diagrams to describe particle interactions and transformations?
3.Go into more detail about the CPT symmetry and possible consequences of a CPT breaking.
4.Discuss quantum fluctuations.

Future Accelerators

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Curriculum & classroom connections

Basic principles about acceleration are introduced in most curricula together with basic electromagnetic interactions about linear and circular acceleration. In some countries photoelectric effect, Compton scattering, pair production and annihilation, wave nature of particles, wave particle duality, uncertainty principle, ionization, plasma, basic forces of nature, key features and components of the standard model of matter including hadrons, leptons and quarks to introduce particle physics and the requirements for larger amount of energy in order to have interactions between elementary particles are all introduced at an entry level. The discussion about the necessity of future accelerators and the ways that new technologies can work are not part of our curricula. Especially phenomena like wakefield acceleration. But still some of the future accelerators use basic physics and that can be a ideal closure for that thematic in a scool presentation.

Key ideas

Future high energy colliders

- Pushing the energy limits to new heights. With higher energies, the scope for discovery of new elementary particles with greater mass expands perhaps fulfilling current or future theories about the existence of super symmetric particles
- Higher levels of luminosity. After introducing students to higher energy thresholds, their understanding for higher luminosity will be supported. With higher luminosity, a greater level of precision for the colliding beam at the interaction points can be achieved.
- Introduction to stronger and superconductive magnets which would increase the strength of the magnetic field which will focus the beam with greater degree of precision
- Basic principles of lasers and it‘s interaction with matter
- Build on a basic understanding of plasma in the context of wakefield acceleration
- The race for future accelerator theory and application

Factors for consideration

- Economic factors (size versus cost)
- Technical options (new technologies can achieve high energies with reduced size)
- Social and cultural factor (what is more important to spend money on; international versus national programmes, medical applications, making new materials, analysing paintings, cleaning pipes)
- Particle choices (leptons or hadrons or muons)
- Hopes for the future (neutrino or muon acceleration)

Best practice example

Methodology practice:
1.Elicitation – Attract the attention of the pupils about the subject
Photos or simulations of future accelerators

2. Thoughtshower – Hypothesis (Check ideas of pupils)

How to build future accelerators?
Why to build future accelerators?
How to build a stronger accelerator?
How will future colliders helps us to better understand the universe?

3. Experimentations – Project based learning

Experiment with circular accelerators (salad bowl accelerator) and linear accelarators (plastic tube).
What to change in order to achieve a larger velocity.
A collider construction competition that takes the cost of materials into consideration.
Build your own particle accelerator (based on cathode tube)
Design the best accelerator of the future (art contest or using software)
Debate about the best idea for future accelerator

4. Conclusion (of the hypothesis)

5. Engaging pupils in project based learning about the applications of future accelerators in everyday life e.g. medical applications, clearning pipes, analysing paintings, making new materials, food irradiation.

6. Conduct outreach programmes to collaborate with other schools, nationally or internationally, to share ideas.

Sources

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