JUNIOR

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Missing particles

Part 1

Picture: Pixabay

Missing particles

Aalto Junior x CMS open data

- **Particle physics-themed workshop, where data is analysed by coding (Python-coding in a Jupyter notebook)**

- **Workshop consists of 2 parts**
  - → **Part 1: predata before the workshop (e.g. at previous lesson or as a homework), materials are in this slide show**

  - **Part 2: practical part (slides and coding activity)**

  Detective skills of the group are tested, when summerstudent at CERN invites them to help to identify real data. Luckily, even large data amounts are not so difficult to handle when you have right tools at use!

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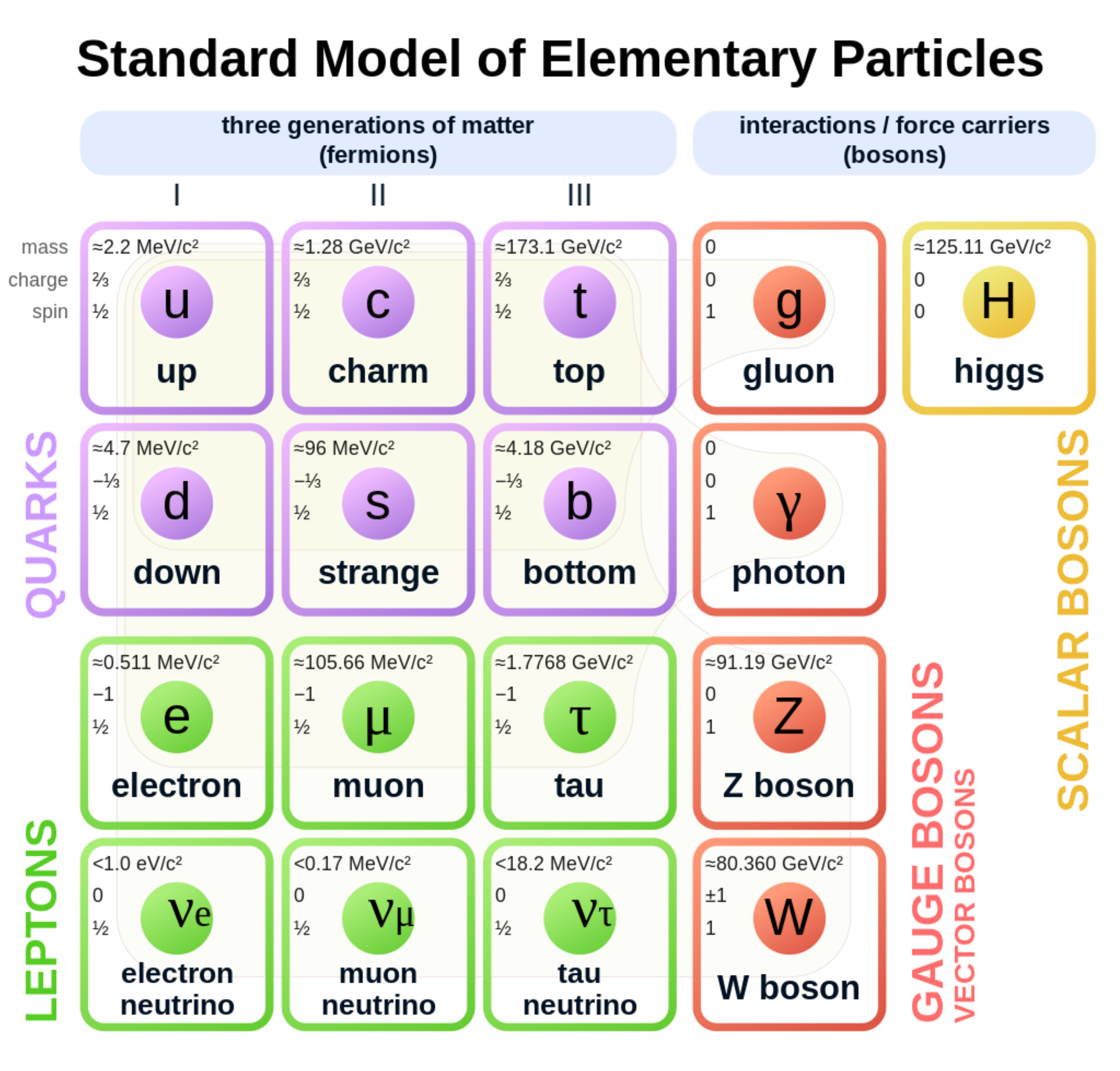
About particle physics

What is gravity ? What is mass? Where did antimatter disappear after the Big Bang, leaving behind the Universe consisting of matter?

- **Particle physics studies answers to fundamental questions about the structure of the Universe and everyday interactions.**
- **Molecules and atoms are common ”building blocks” of Science, and they are easy to observe. But in order to be able to get answers, we have to investigate what kind of building blocks molecules and atoms are made from.**
- **These blocks are elementary particles** (=**fundamental particles**)
  - **They do not have inner structure: they do not consist of other particles**
  - **Extremely small in size, no direct detection method**
  - **Most of them cannot exist as free particles in natural conditions**
- **Standard model is made of elementary particles**

Elementary particles

- **All atoms in the Universe consists of elementary particles**
- **12 different types, but in natural conditions occurring today only 4 of them exist – electrons, neutrons of electrons, up-quarks, and down-quarks.**
  - **Other particles existed in the nature immediately after the Big Bang, because their creation requires high energy levels. Typically it can happen only due to cosmic radiation, or in particle accelerators.**
- **Elementary particles are organized as a part of the standard model, which tries to explain what materia is made of and which interactions take place in it.**



Picture: https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

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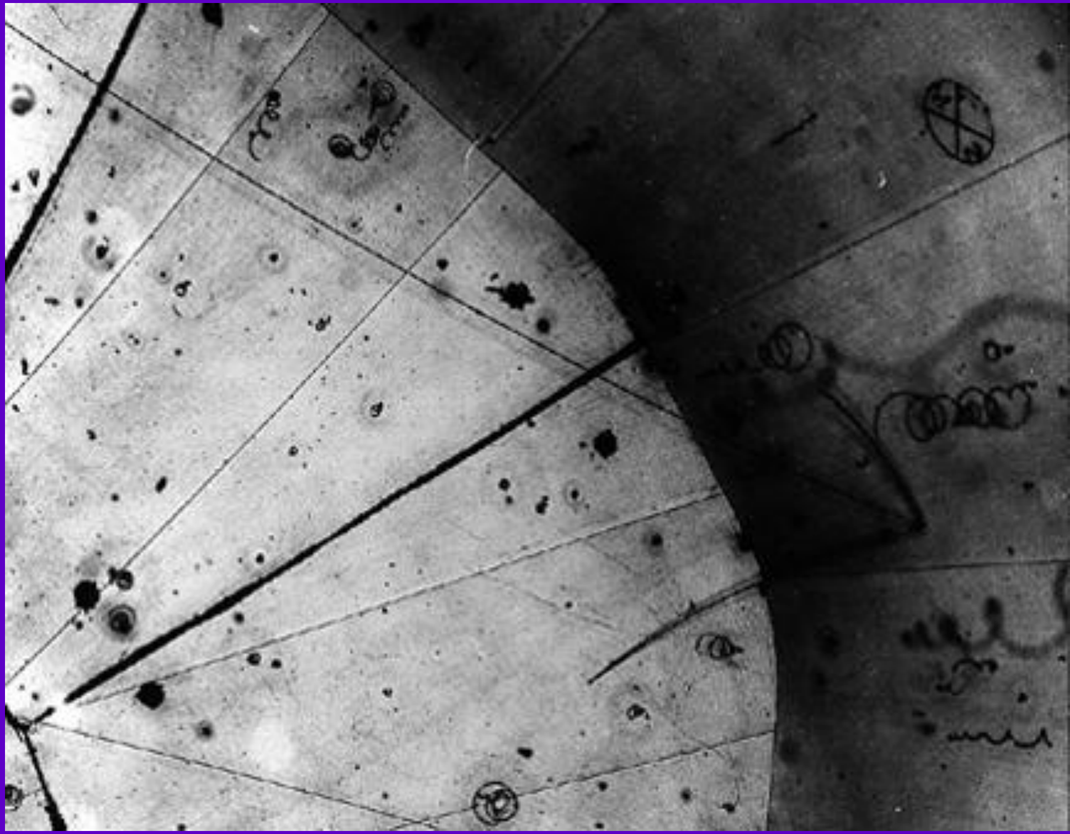
Standard model opened(1/2)

Fermions can be separated roughly into two different categories: quarks and leptons

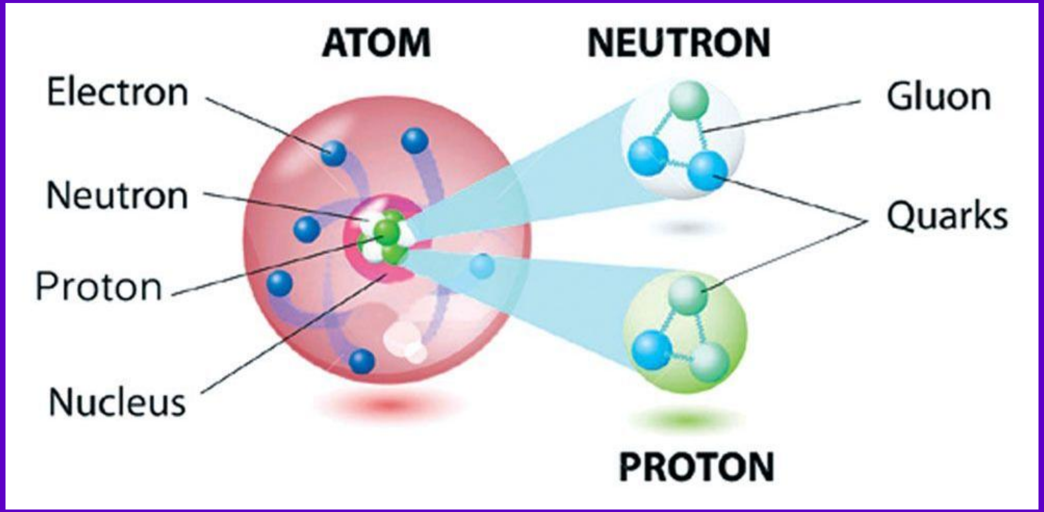
- Quarks are subatomic particles
  - 6 different types: up, down, strange, charm, top, and bottom
  - They form hadrons, strongly interacting composite particles e.g. protons and neutrons.
- Leptons are also elementary particles.
  - 6 different types of leptons: Electron, myon, and tau, and electron neutrino, myon neutrino and tau neutrino
  - Only electrons are building blocks of regular materia.



Picture is presenting the first neutrino observation photographed (1970)

Picture source
https://commons.wikimedia.org/wiki/File:First_neutrino_observation.jpg

Standard model opened (2/2)



Force carrier particles, bosons, keep "building blocks" together . They mediate four of nature's basic forces to atoms:

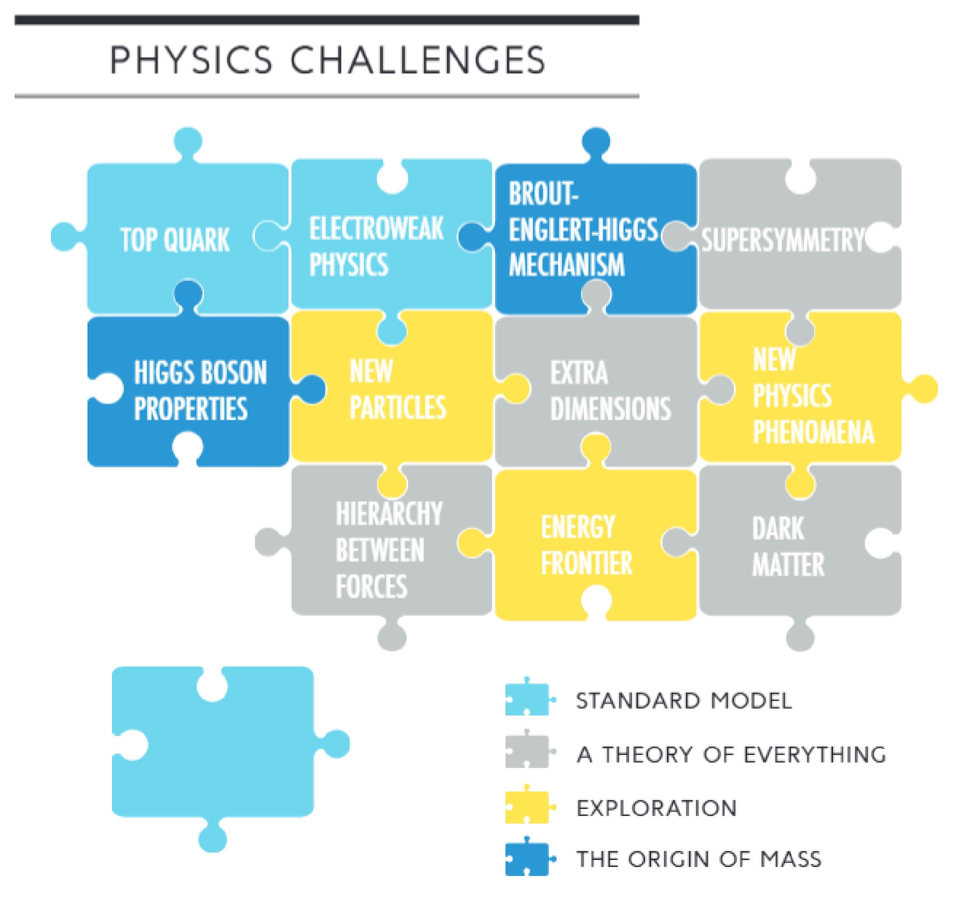
- Photon is massless light particle, which mediates electromagnetic force.
- Gluons glue quarks together in elementary particles and mediate strong nuclear force
- W- and Z-bosons mediate weak nuclear force. They are related to certain kind of forms of radioactivity.

In addition, there is Higgs boson. It was found with 99,99% likelihood year 2012. Higgs boson gives mass to the building blocks of atoms. Quarks are attached more strongly to Higgs bosons, and that is why they are heavier than the electrons.

Standard model

- Matemathical model, which describes:
  - Known elementary particles
  - Weak and strong interaction
  - Electromagnetic interaction

- Standard model is not ”theory of everything”, some small pieces are missing from it. After the detection of Higgs boson, its qualities have been studied intensively.



Picture: https://home.cern/science/physics/standard-model

What is a model?

Model is a simplified description of the reality. Models in physics are built as collaboration of theory and experimental research. Theoreticians build models, which are tested experimentally and modified as research evolves and new parts are found to the puzzle.

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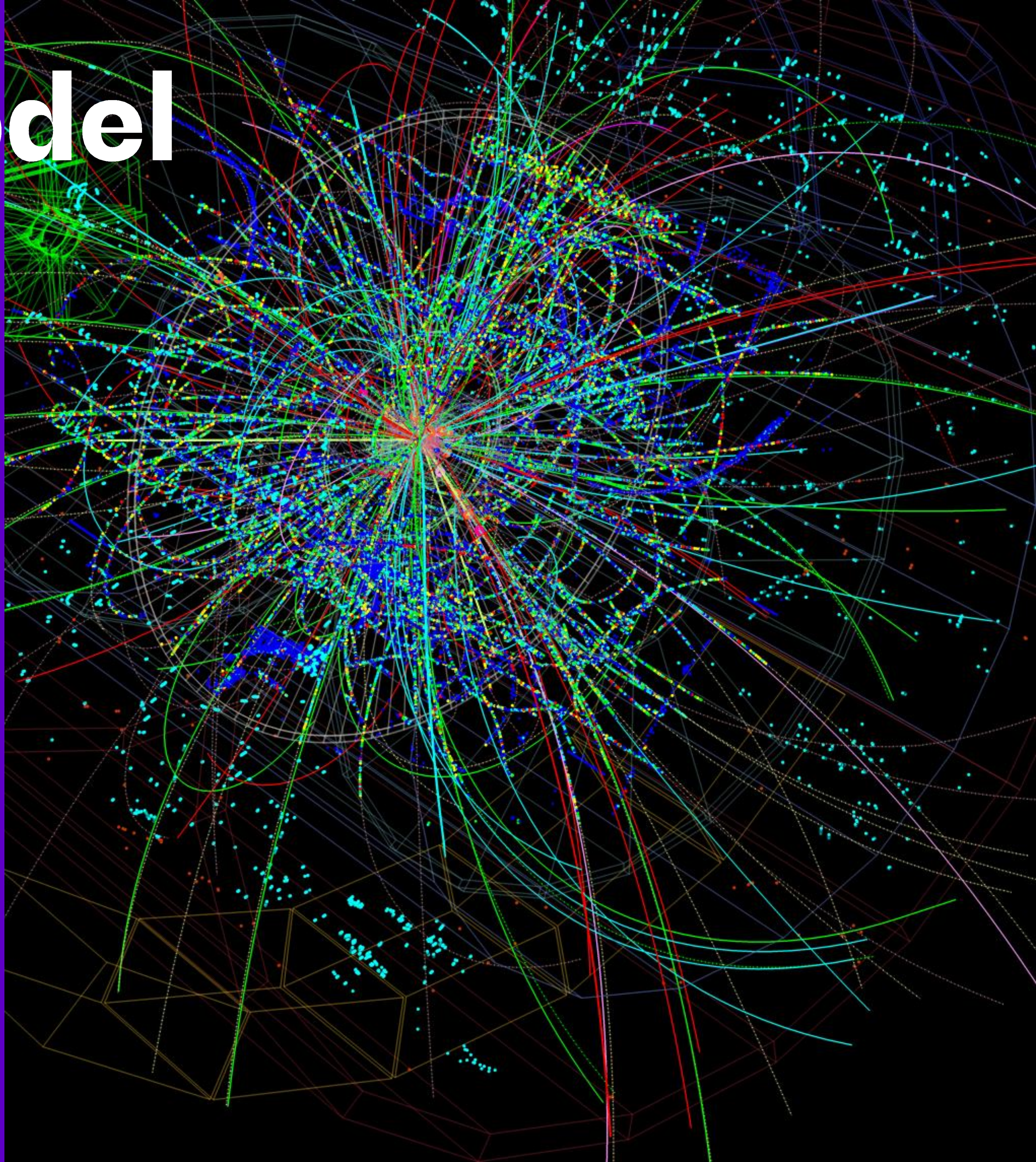
Standard model

What standard model does NOT explain:

- Is the Higgs boson found like it should be according to the standard model? Is it the only one?
- Why is there so much more materia than antimateria in the universe?
- How to explain mass of neutrinos?
- What is dark matter?
- How about dark energy? How is gravitation linked to other (quantum) interactions? Is there only 3+1 dimensions?
- Why is there 3 particle families? Do the "elementary particles" have inner structures? Is there more symmetries in the nature? Supersymmetry?

→ There is research to be done



Studying particle physics (1/2)

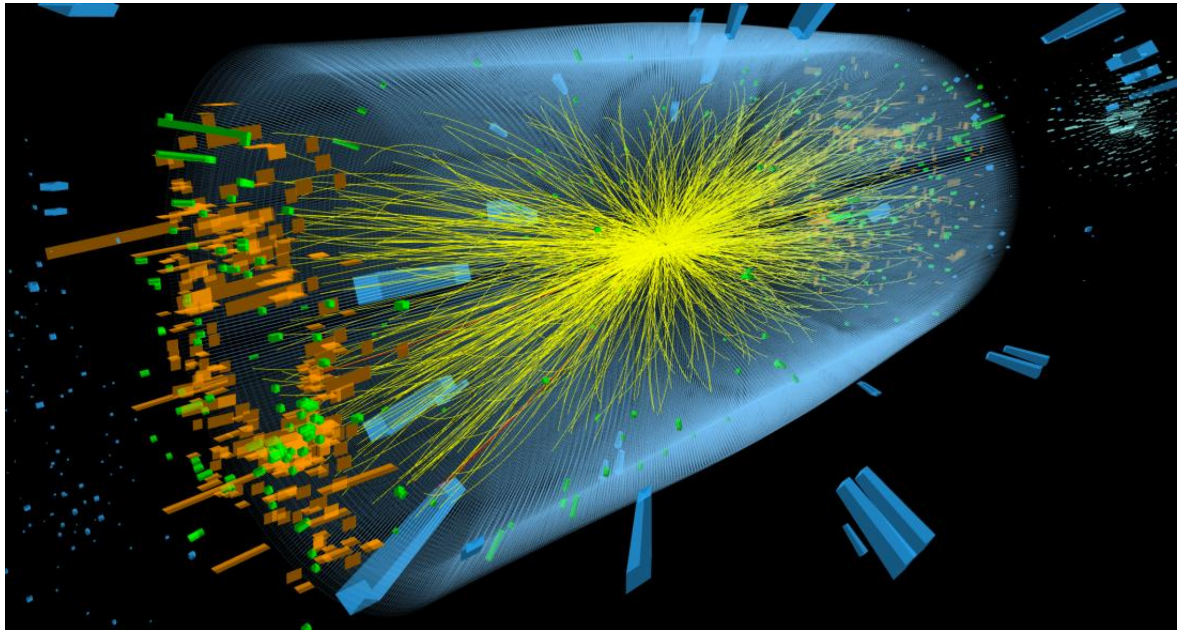
If particles do not exist naturally, how can you study them?

"[Other elementary particles] existed in the nature only immediately after the Big Bang, because the formation of particles demands very high energies."

...one must replicate conditions like there were during the Big Bang, when there was a lot of energy, and particles can be formed!

→Acceleration and collision of particles in particle accelerator, when particles will break up into elementary particles.

Particle physics is also called high energy physics



Studying particle physics (2/2)

- Experimental research in particle physics is indirect and data is collected a lot, so that with the help of probabilities, results and new observations are made.
  - Results are confirmed with statistical tests, e.g. calculating p-value or standard deviation (sigma, σ)
  - Compare: In Biomedical research typical ”approved” limit for statistically signicant result is ($p < 0.05$), two sigma p-value. In Quantum physics, the aim is much smaller value, ($p < 0.0000003$), five sigma p-value.

- LHC generates about 90 petabits of data yearly in its different research stations.
  - “One petabit (PB) is thousand terabits. To store all about 50 000 movies in the world at “studio quality”, 10 petabits are needed.”

Does “statistically significant” also mean “scientifically important”?

More info: https://blogs.scientificamerican.com/observations/five-sigmawhats-that/

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Particle accelerator

Short presentation video about CERN, particle physics research center in Europe.

- **Research instrument is particle accelerator LHC, Large Hadron Collider**
  - **Collides hadrons, as protons and neutrons :D**
- **Several *detectors, e.g.* CMS, compact myon solenoid**

Video is slightly old; LHC was on its second long maintenance and upgrade shutdown (2019-2022). LHC will now operate at an even higher energy and, it will deliver significantly more data to the upgraded LHC experiments.

https://www.youtube.com/watch?v=S99d9BQmGB0

Particle accelerator

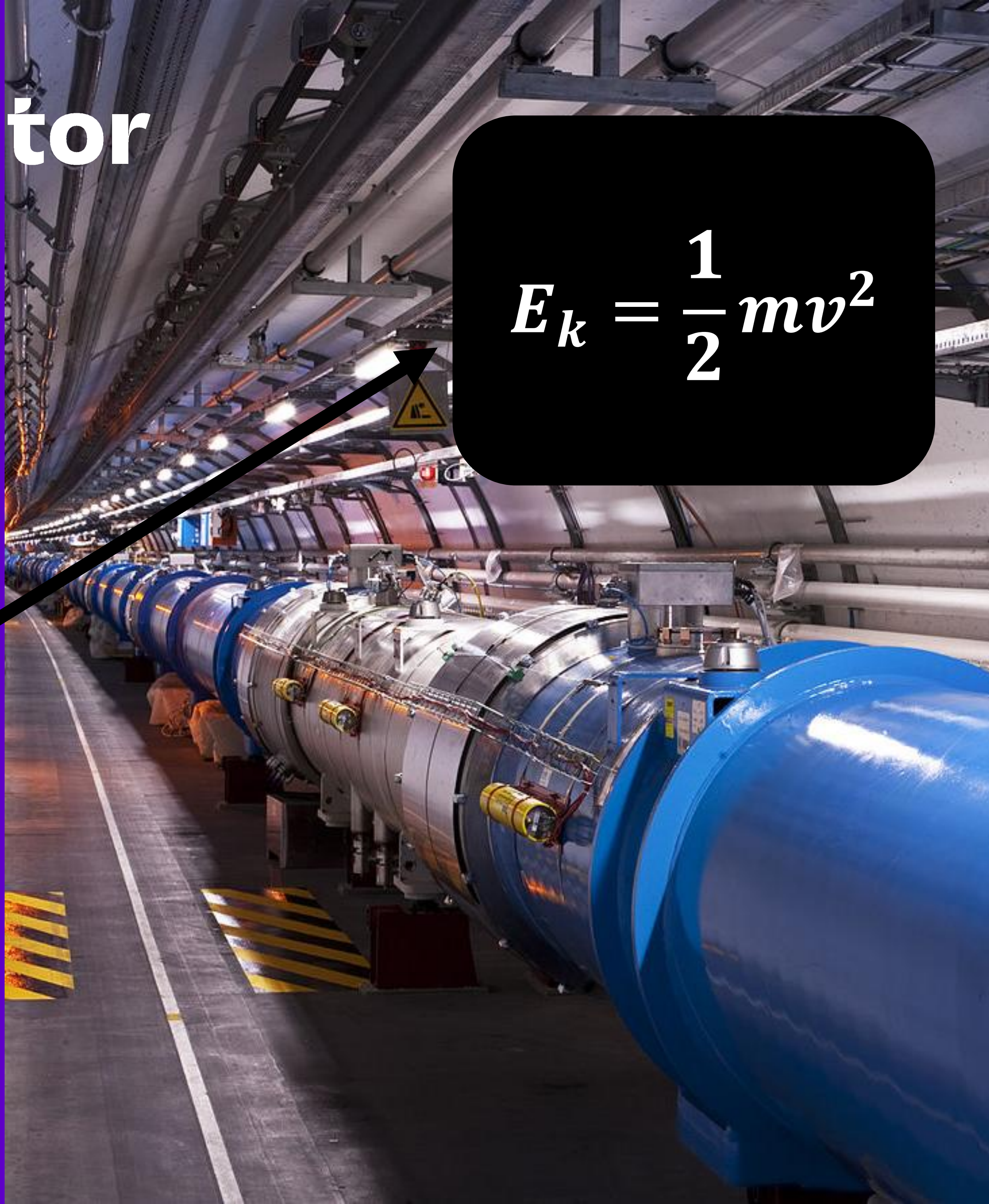
- **Particle accelerator is, as simplified, a vacuum tube, with voltage created inside it, which creates movement of the charged particles.**
  - Electric field accelerates and magnetic field directs.

- **LHC collides protons travelling almost at the speed of light.**

  → Energy grows when speed grows (kinetic energy equation…)

- **In these large energy collisions, new particles may form which diverge to different directions.**

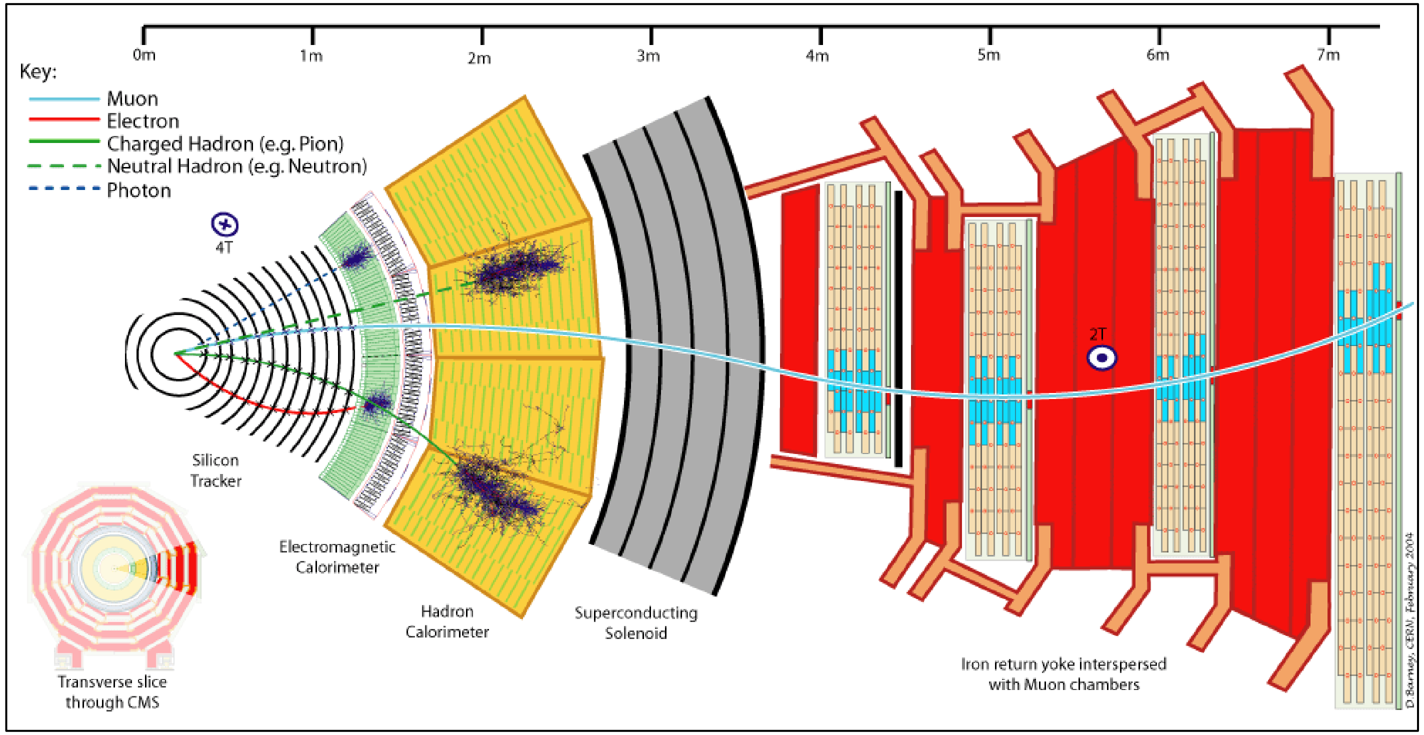
- **The aim of the detector surrounding the collision point (e.g. CMS), is to measure charges of the particles formed, trajectories and energies, so that particles are able to be identified.**



$$E_k = \frac{1}{2}mv^2$$

Measuring particle data with CMS detector

Different particles interact with matter in different ways.
→ From the measured quality it is possible to conclude which particle is in question.
CMS (compact myon solenoid) is like an onion– its different layers detect different qualities, that particles have (e.g. electric charge).



Studying particle physics – Units (1/2)

Planck's constant: Natural constant, which combines units of frequency and energy together (E = hf)

$$\hbar = \frac{h}{2\pi}$$

$$= 1.055 * 10^{-34} Js$$

- **In the world of quantum physics basic laws of mechanics are not valid when mass changes to energy and vice versa. That is why units like meter and kilogram are not useful for particle physicists…**

- **Speed is approaching the speed of light, v ~ c**
- **Energy and momentum are much bigger than mass, E >> mc^2, p ~ E/c**

- **Commonly this presumption is made: $\hbar$ = c = 1**
  where c = speed of light and $\hbar$ = the reduced Planck's constant
  - **Change can be made, because the speed of light (in a vacuum) is a constant and its numeric value is dependent on selected unit of presentation.**
  - **Same change has an effect on the system at use, so that speed becomes dimensionless, it has no unit. That is why also units of momentum and energy changes:** $p = m * v \rightarrow p = m$
    $E = m * v^2 \rightarrow E = m$
- **With the presumption c = 1, several other formulas can be cleaned (e.g.** $E = mc^2 \rightarrow E = m$)

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Studying particle physics – Units (2/2)

- **Conservation laws apply. We can form quantity invariant mass (m_0) with the help of energies and momentums of particles.**

$$m_0 = \sqrt{(E_1 + E_2)^2 - \|p_1 + p_2\|^2}$$

- **When a particle splits (= ceases to exist), its mass before fission can be calculated from the energies and momentums of fission products. Reference frame, where energies and momentums were measured, do not have effect on the inferred value of mass. It is independent, invariant mass.**

→ **Invariant mass remains when a particle splits into new particles.**
  - **If it is calculated to daughter particles formed in a specific collision, an estimate is made which is close to the mass of mother particle.**
  - **If we calculate invariant mass to particles that are not related to each other, we get a value that does not describe anything, it is basically background noise.**

- **Energy, momentum and invariant mass are expressed in a common units of energy, electron volt (eV) = 1.602176634×10^{-19} Joule**

More information: https://profmattstrassler.com/articles-and-posts/particle-physics-basics/mass-energy-matter-etc/mass-and-energy/

Particle physics

- All particles cannot be detected with CMS. E.g. neutrinos are detected undirectly via conservation of momentum

→ Research of events of collision is like making a puzzle, where data collected with different detectors is combined together.

- In the collisions with high energies, new particles can be formed and part of them are stable, and part of them unstable.
  - Because unstable particles exist only a short time, particle detectors cannot detect them.
  - We have to study the qualities of the particles to be able to know what particles were formed in the collision.
- Data collected by particle accelerators tell us the energy and momentum of formed particles. We can calculate the mass of particles splitted with the help of these quantities.
  - But how is it done?

– Trajector (Traces of charged particles)
– Calorimeter (energy)
– Detectors measuring specific particles
– Setting detectors inside the magnetic field

Particle physics

→ Invariant mass remains, when particle splits into new particles.

- E.g. If collition of two particles creates six particles, the sum of invariant mass of these two particles sum of invariant mass of daughter particles.

- Making one observation is never enough. It is important to examine results critically and get to measure statistically important amount of data, so that real phenomena stand out from the background noise.

- When enough data is collected, e.g. histograms can be used to visualize results.
  - To be able to determine where stable particles detected at the splitting of a heavier particle, researchers study large amounts of collision data.

Challenges...

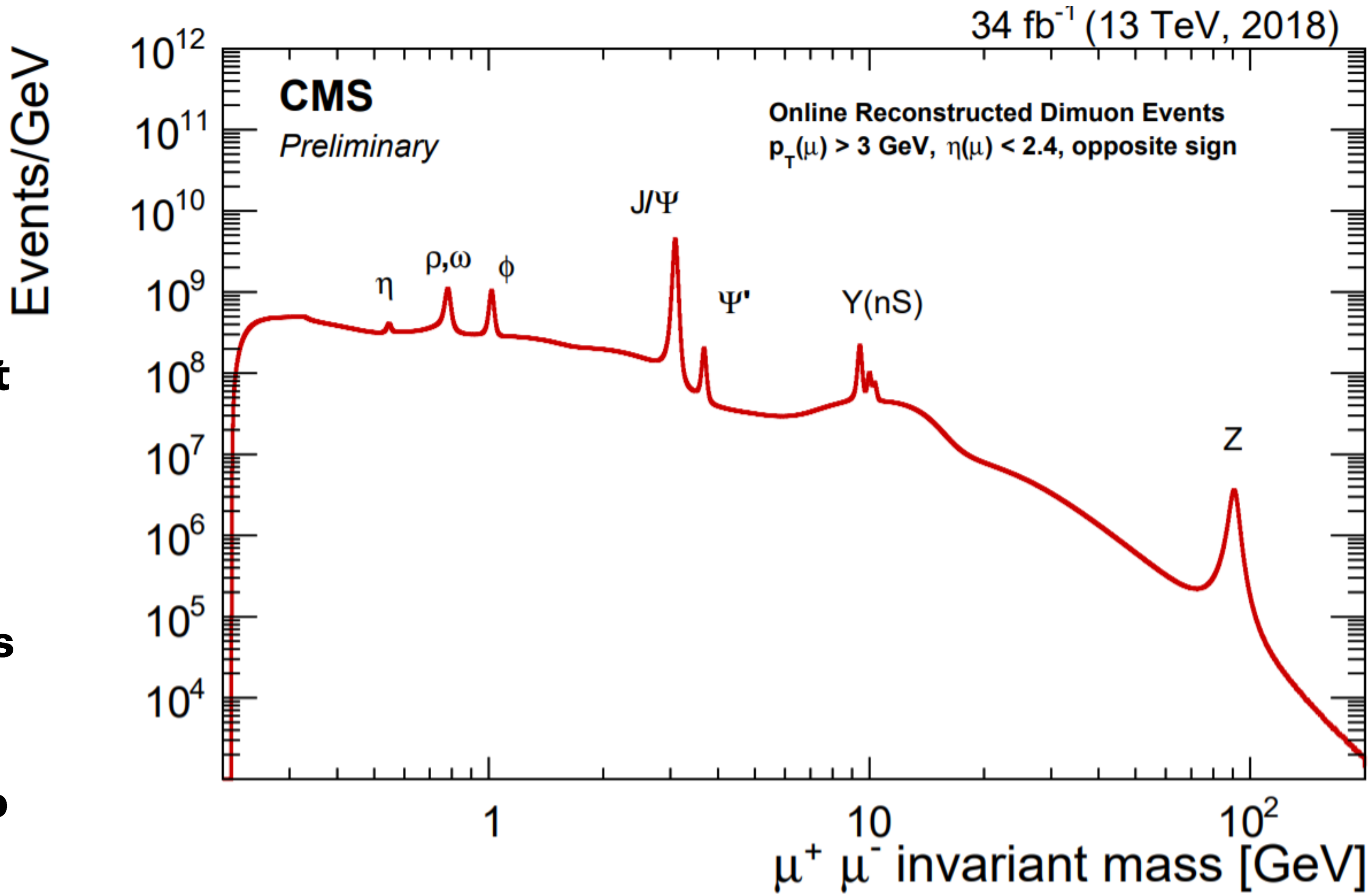
- Trigger challenge: How to select 400 events from 20M events each second, saving only events that are interesting from the point of view of modern physics?

- Computing challenge: how to store 400 events per second each second? How to store over a hundred petabits data per experiment? How to analyse that amount of data?

- Data analysis challenge: how to maintain good particle reconstruction and recognition efficiency in spite of simultaneous events.

Particle physics

- **Spikes in the histogram of invariant mass may refer to mother particle of specific energy.**
- **To be able to draw histograms, a huge amount of data is needed, in particle physics billions of datapoints.**
- **Note the logarithmic scales on the adjacent histogram!**
- **Histogram is a good way to present proportional change instead of absolute change**



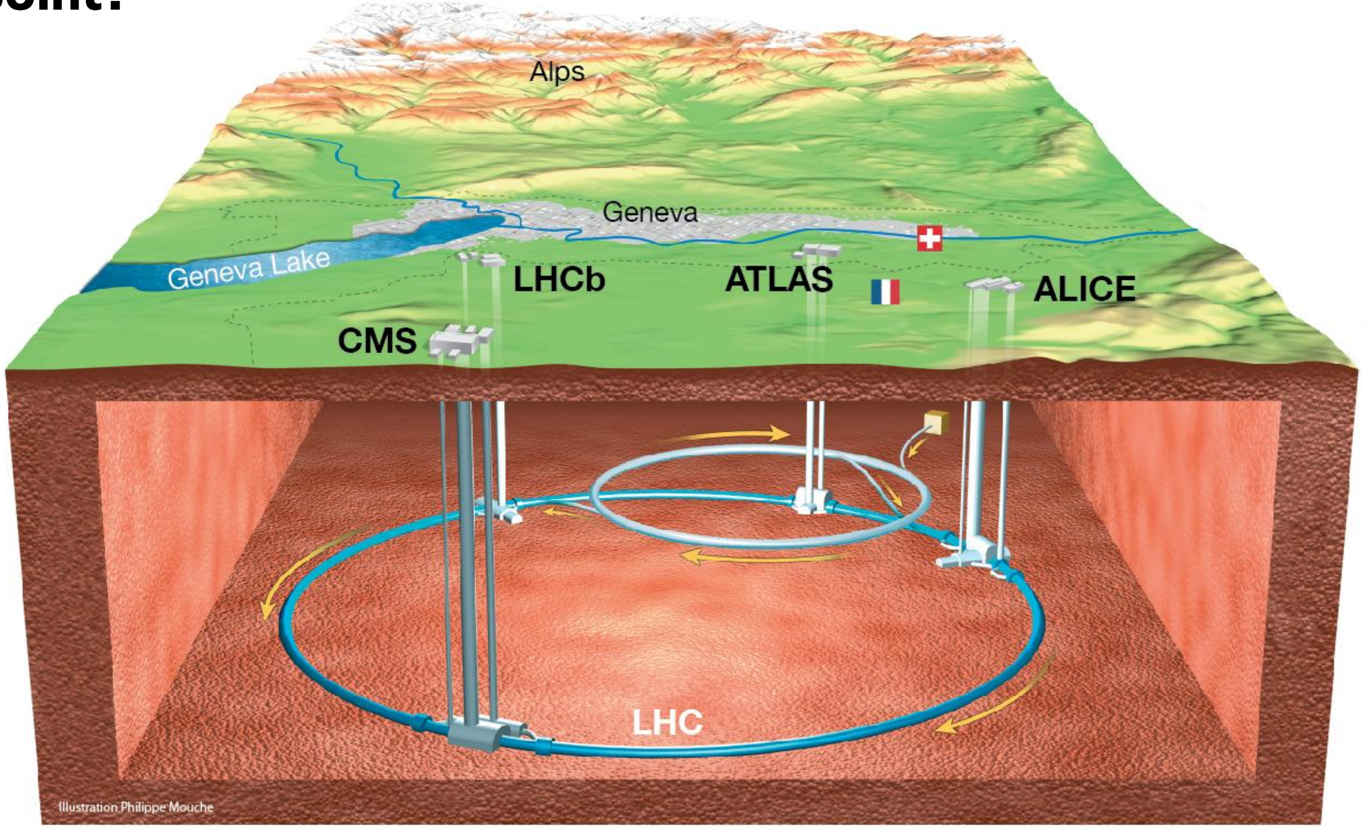
Invariant mass distribution of collisions where the detector has registered two muons from years 2017 and 2018. Spikes of particles able to split into two muons, are easy to see from the distribution.

Exercises

Question 1: Particle accelerator

If a particle spins clockwise in LHC, in which direction should the magnetic field point?

A: upwards
B: downwards
C: clockwise
D: counterclockwise



Hint: Right hand rule

Question 2: Electron volt

Ionization energy for hydrogen atom is 2.195×10^{-18} J.

a) How much is this energy in electron volts?

b) Calculate the hypothetical mass for this ionization. (Hint: $E = mc^2$)

Thank you!
You are now ready to open part 2 slides.

Answers Q 1: Particle accelerator

If a particle spins clockwise in LHC, towards which direction should the magnetic field point?

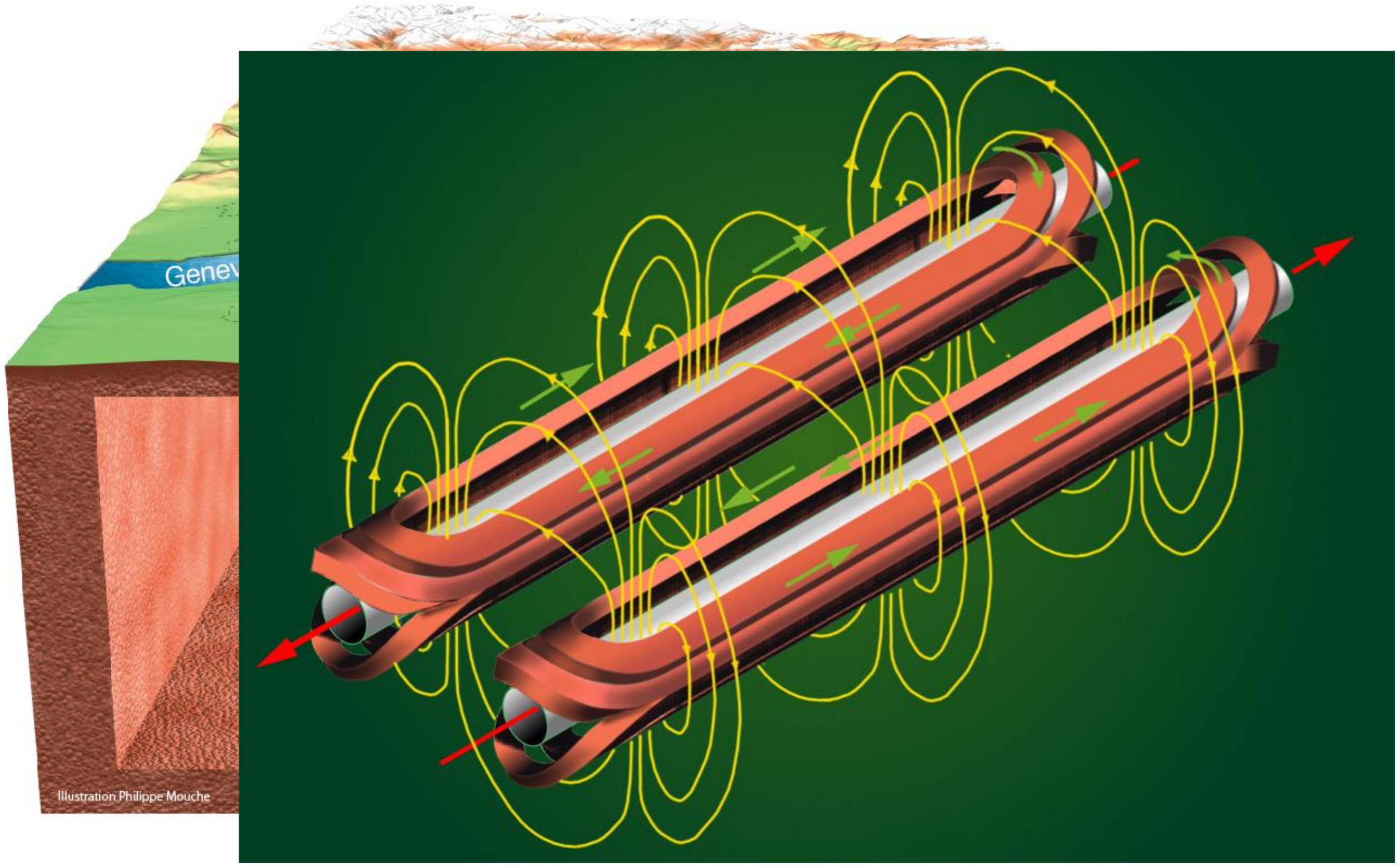
ANSWER:

A: Magnetic field needs to point *upwards* so that the force it induces, keeps the proton moving in a circular path.

In LHC accelerator, protons are accelerated to both directions.

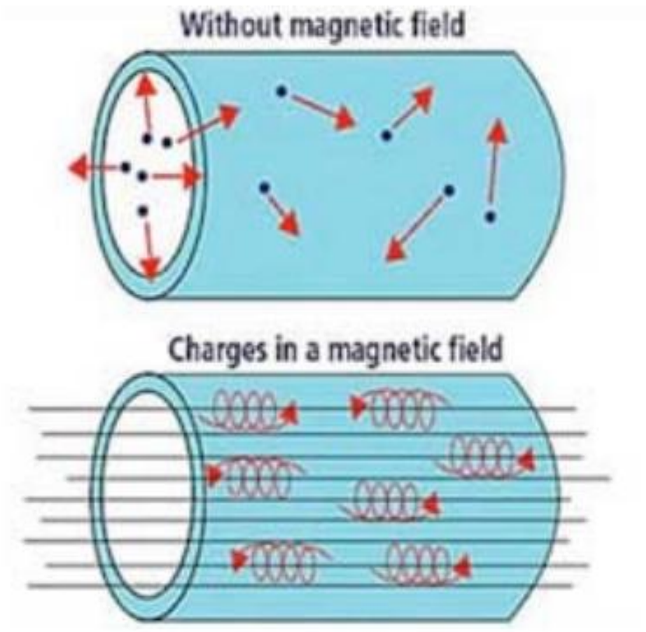
Magnetic field points downwards in another tube where the proton move counterclockwise.

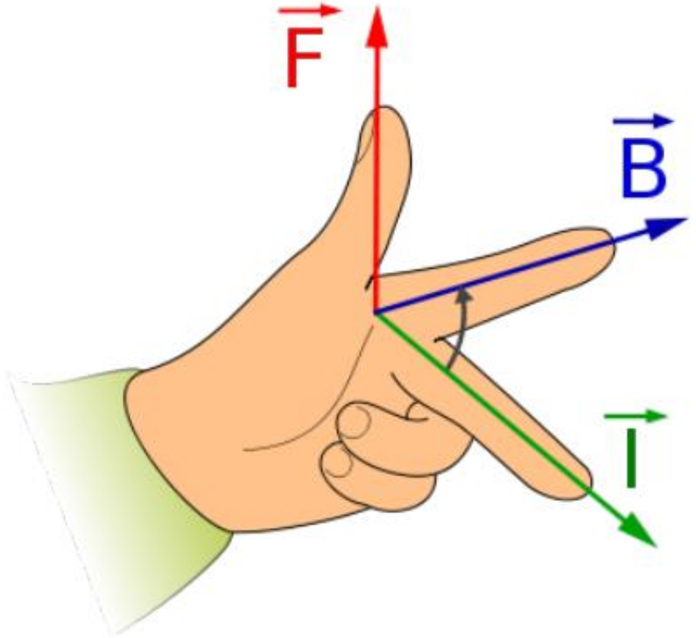
Hint: Right hand rule



Hiukkanen magneettikentässä

- Varatun hiukkasen rata kaareutuu magneettikentässä:
  - ***F*** = *q* **v** x ***B***
  - Risti- eli vektoritulon suunta oikean käden säännöllä ***X*** x ***Y*** = ***Z***
  - ...tai vasemman käden muistisäännöllä **F.B.I.** (*I*=*qv*)
- Yhdistämällä Newtonin toinen laki, $F = ma$, keskeiskiihtyvyys $a = v^2 / R$ ja $p = mv$:
  - ***p* =** *q****RB*** eli suurempi liikemäärä vastaa suurempaa kaarevuussädettä





Slide: Mikko Voutilainen

Answer Q 2: Electron volt

Ionization energy for hydrogen atom is 2.195×10^{-18} J.

a) **How much is this energy in electron volts?**

b) **Calculate the hypothetical mass for this ionization. (Vinkki: $E = mc^2$)**

Answer a):

$$2.195 * 10^{-18}\ J * \frac{1eV}{1.602 * 10^{-19}\ J}$$

= 13.7 eV

Answer:
Ionization energy for hydrogen atom is 13.7 eV.

Answer b):

$m = E/c^2$
$c = 2.99792458 \cdot 10^8$ m/s

$$1\ \mathrm{eV}/c^2 = \frac{(1.602\ 176\ 634 \times 10^{-19}\ \mathrm{C}) \times 1\ \mathrm{V}}{(2.99\ 792\ 458 \times 10^8\ \mathrm{m/s})^2} = 1.782\ 661\ 92 \times 10^{-36}\ \mathrm{kg}.$$

Answer: 1.78×10^{-36} kg
Note: result should be multiplied with 13,7eV; which is missing from the formula! -> 1.78×10^{-36} kg x 13,7

Next slides are not part of the workshop, but they may be interesting to take a look at.

Extra information about the functions of different layers of CMS

Trace detector detects routes of reserved particles, when they interact electromagnetically with the detector. Collision points of prontons and splitting points of heavier nuclei can be determined with very specific spatial data. Particle momentum can be calculated with the help of radius of curvature of particle's trajectory.

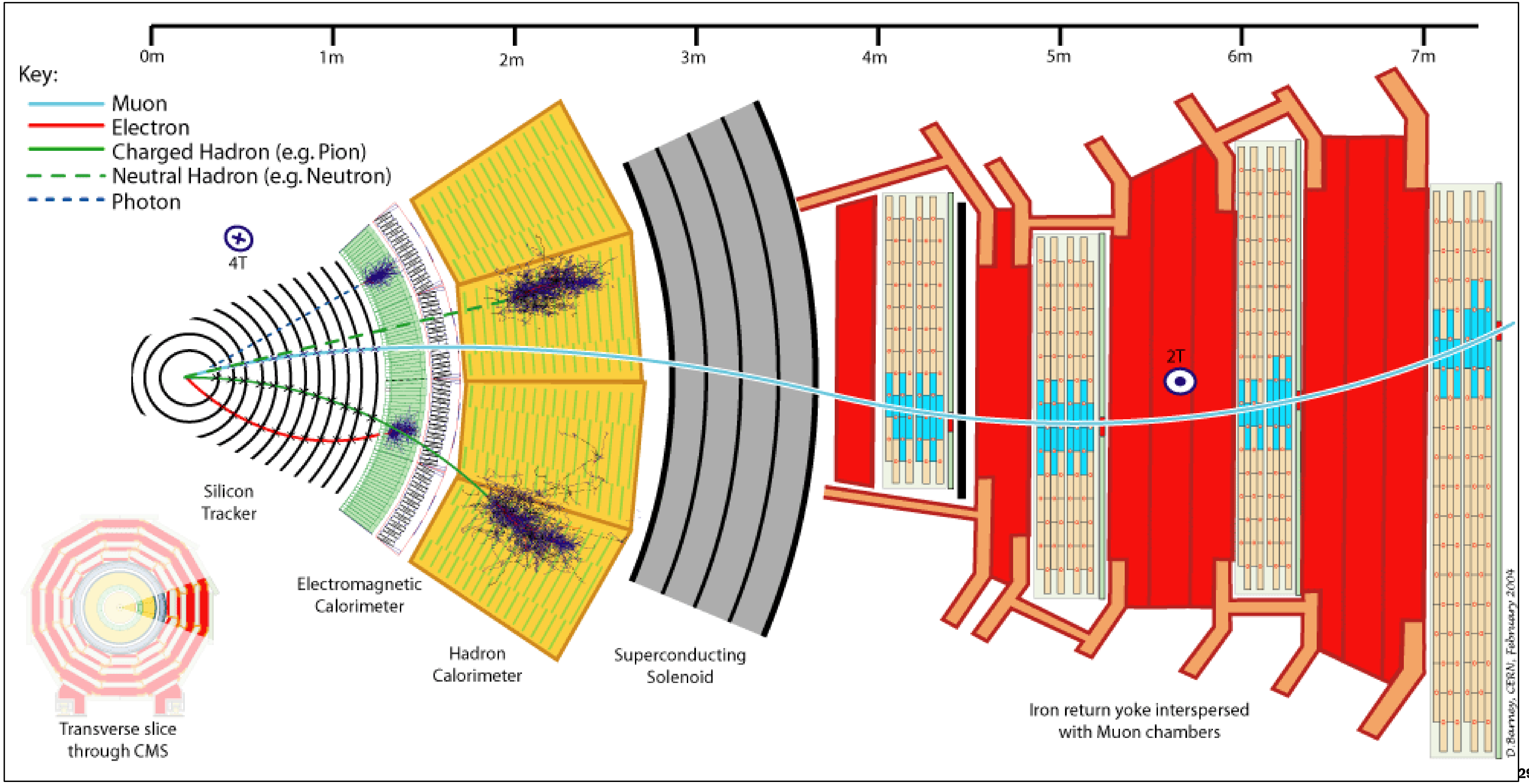
The Electromagnetic Calorimeter (ECAL) measures the energy of electrons and photons by stopping them completely. When electrons and photons collide into ECAL-layer, it creates electromagnetic radiation, which is measured with scintillation detectors. Energy of the collided electron or photon is directly proportional to the amount of light detected by scintillation detector.

Hadron calorimeter (HCAL) stops particles called hadrons like protons and neutrons. Hadrons entering HCAL-layer lose their kinetic energy to particle torrents, which are measured with scintillation detectors. With the help of the amount of reactions measured, the original energy of hardon particle can be calculated.

Myonijärjestelmä
Muons are hard to detect and they travel through ECAL and HCAL layers without losing their energy. Muon detecting chambersare placed in the outer part of the experiment where they are the only particles likely to produce a clear signal. Muons are positively charged particles, so when they travel through gas filled chambers (drift tubes), gas in the chamber get ionized. Electrons released in ionization and positive ions drift to anodes and cathodes (cathode strip chambers). From the recorded signals, location of one muon on specific time point can be calculated.

All particles cannot be detected with CMS. For example, neutrinos are detected indirectly via conservation of momentum energy.

Examine how different particles act at different layers of CMS detector.
Examine what kind of charge the particles shown in the picture have.



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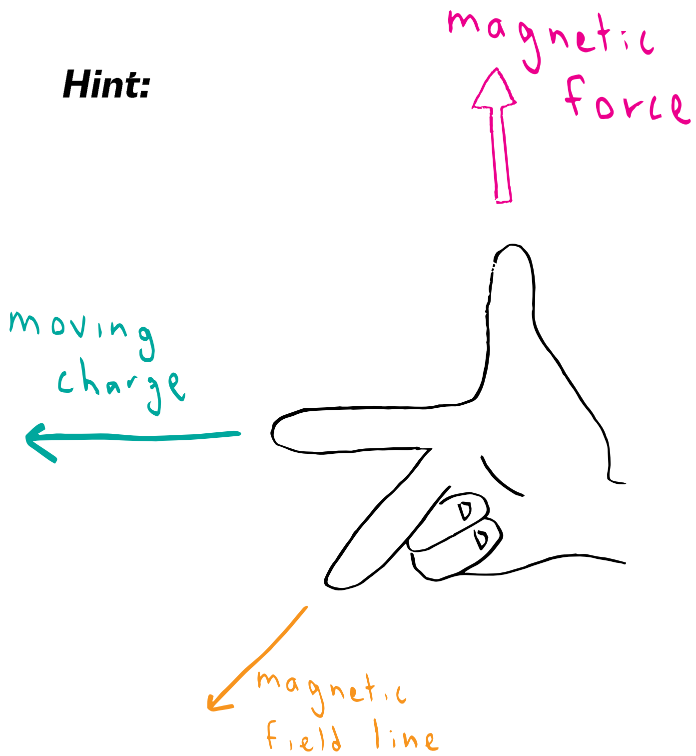
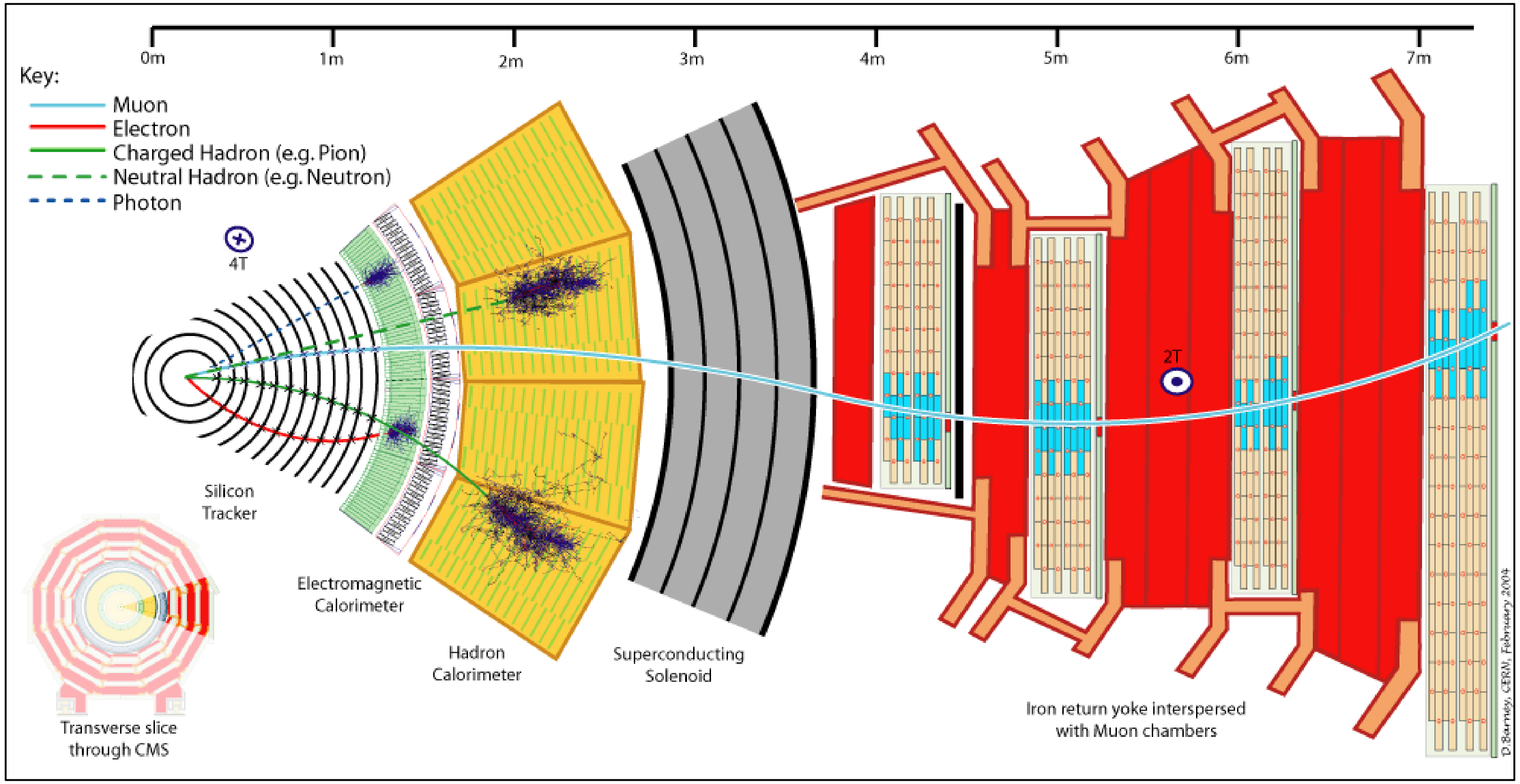
Examine how different particles act at different layers of CMS detector. Examine what kind of charge the particles shown in the picture have.

Hint:





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Examine how different particles act at different layers of CMS detector.
Examine what kind of charge the particles shown in the picture have.

ANSWER:

Muons are hard to detect , but CMS (Compact Muon Solenoid) is very good at it too. Muons travel through all layers without stopping, but they leave signals to silicon trackers and to muon chambers. In the picture, the trajectory curve of the myonin rata turnes first downwards and then, after passing a strong solenoid magnet, starts to bend upwards. According to the right hand rule, muon is negative particle. Pay attention to, that inside the solenoid magnet, the magnetic field is towards opposite direction compared to the magnetic field outside the solenoid magnet.

Electron's trajecotry curves are upward in the picture. According to the right hand rule, we end up to conflict. A particle acts like positive charged particle, but we know that electrons are negatively charged. In this case we are talking about positron, antiparticle resembling electron but with a positive charge.

Hadrons: In the picture, two hadrons are marked, other with a green line, and other with a green dashed-line. Hadrons are particles formed by two quarks at minumum.

- Trajectory curve of the particle marked with a green dashed-line, does not bend at all at 4 Teslas strenght of 5 magnetic fields (about 100,000 times Earth's magnetic field). This means that hadron is chargeless. It can be e.g. neutron. Speed of the neutron is slowed down at the hadron calorimeter, when it interacts wiht materia and creates a signal.
- Trajectory curve of the particle marked with green line bends downwards in the picture. We can assume that this particle is negatively charged. This hadron is e.g. Pion ($\pi-$:$d\mu$——), momentum of hadron can be measured from the burst of particles it caused at the hardon calorimeter.

Movement of photon inside CMS is drawn with dark blue dashed-line. Line is straight and ends into particle burst at electromagnetic calorimeter. Photon is chargeless.

Materials of this workshop

Creator: Linda Hemmann

Sources:

https://github.com/AaltoJunior/Hiukkaset-Hukassa

A BRIEF INTRODUCTION TO PARTICLE PHYSICS by Nari Mistry, Laboratory for Elementary Particle Physics, Cornell University

https://www.classe.cornell.edu/rsrc/Home/Outreach/TeachingResources/Brief_Intro_to_HEP1.pdf

Editors

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