THE ATLAS EXPERIMENT COLOURING BOOKS

A brief guide for parents and teachers

About the guide

This guide was developed to help you teach kids about the search for fundamental particles. It complements the material available in the ATLAS Colouring books, available here: https://atlas.cern/resources

This book is not an encyclopedia of all of particle physics; instead, it provides a general overview of both the science and the research for non-experts. Many people interested in discussing these topics with kids often feel that their own knowledge is not enough.

This guide will enhance your understanding of the field so that you will be comfortable in sharing your knowledge with kids. It will provide you with a list of resources in case you want to learn more about some topics or just put the knowledge you acquired into practice.

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What is particle physics?

We can define particle physics as the science of the really small things that make up the Universe. This includes leptons (such as the electron), the quarks that make up protons and neutrons, and gauge bosons, which mediate forces between particles.

Particle physics is the study of **fundamental subatomic particles**, or elementary particles, including both matter (and antimatter) particles and the carrier particles of the fundamental interactions. By studying fundamental interactions, physicists try to comprehend how these elementary particles behave alone and with each other.

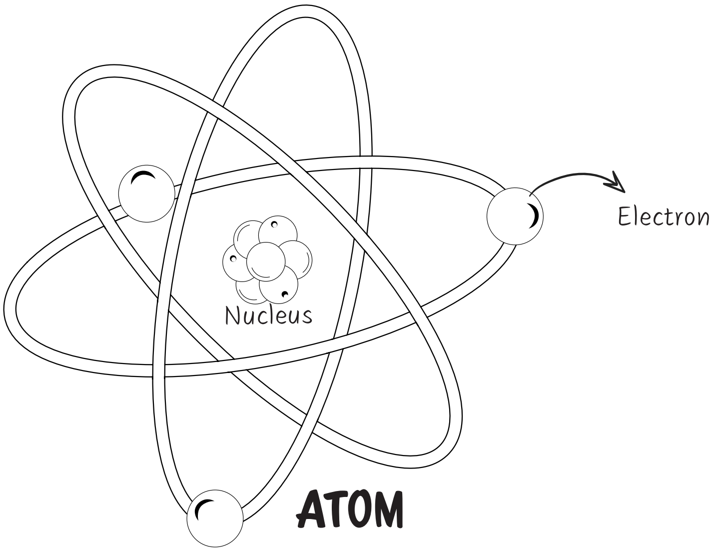
Besides studying elementary particles themselves, particle physicists also **study the fundamental forces** that govern how particles interact and decay. All the known forces of Nature can be traced to these fundamental forces: gravity, weak force, strong force and electromagnetic force.

Our best understanding of particle physics is encapsulated in the **Standard Model of Particle Physics**. This can be compared to the Periodic Table – but for particles and forces. Physicists are constantly testing the limits of the Standard Model, looking for new additions or corrections to this theory. Truth is, science is always working! And one day we might find that elementary particles aren't so elementary after all.

The Standard Model is great at explaining a lot about the Universe, but there is still much that particle physicists do not understand. For example, only three out of four fundamental forces are described by the Standard Model, yet we do not know how gravity fits in? Why are we made of matter and not antimatter? These are some of the **main motivators** for the research carried out at ATLAS.

Particle Physics is sometimes called "**high-energy physics**" as physicists need to smash particles together at very high energies in enormous colliders to create and study some of these particles!

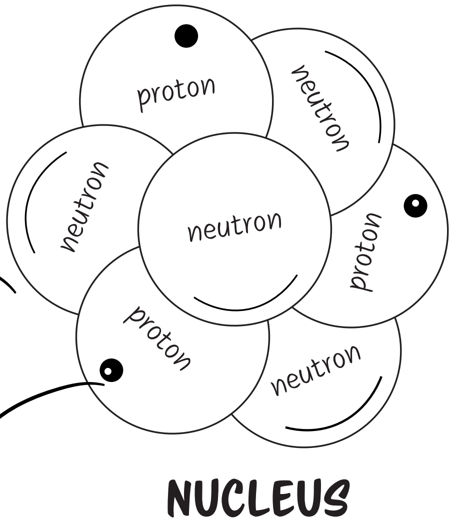
What is an elementary particle?

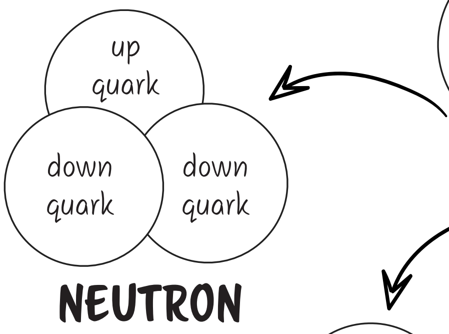


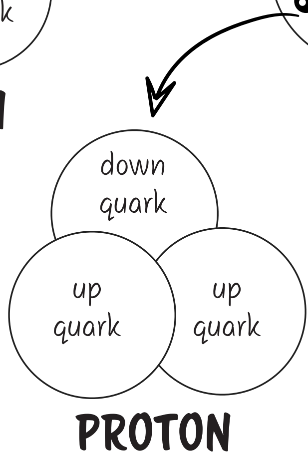
An **elementary particle** is not known to be made up of smaller entities. Elementary particles are the fundamental building blocks of the Universe.

Quarks and electrons, for example, are elementary particles. Although both are elementary particles, electrons and quarks **differ in many aspects**. Whereas quarks together form nucleons (protons and neutrons) within the atomic nucleus, the electrons make up the shell of atoms.

An atom may be **tiny**, but the diameter of the nucleus is ten thousand times smaller than that of the atom. Quarks and electrons are at least ten thousand times smaller than that!







Additional resources

- Questions and facts you can use as examples:
  - Can you identify something that is like a particle?
  - What is the smallest thing you have ever seen? Maybe a grain of sand? The diameter of an atom is about a million times smaller than that of a grain of sand!
  - If an atom was the size of a ping pong ball the nearest electron would be about one kilometer away.

What is the Large Hadron Collider?

The Large Hadron Collider (LHC) is a 27-km circular **particle accelerator** based at CERN in Geneva, Switzerland. It both accelerates and collides particles at record-breaking high energy in order to explore areas not charted by the Standard Model and search for new phenomena.

The LHC is the final link in a **chain of accelerators** with increasingly higher energies. Each injects the beam into the next one, which brings the beam of particles to an even higher energy. Particles in the LHC are accelerated almost to the speed of light.

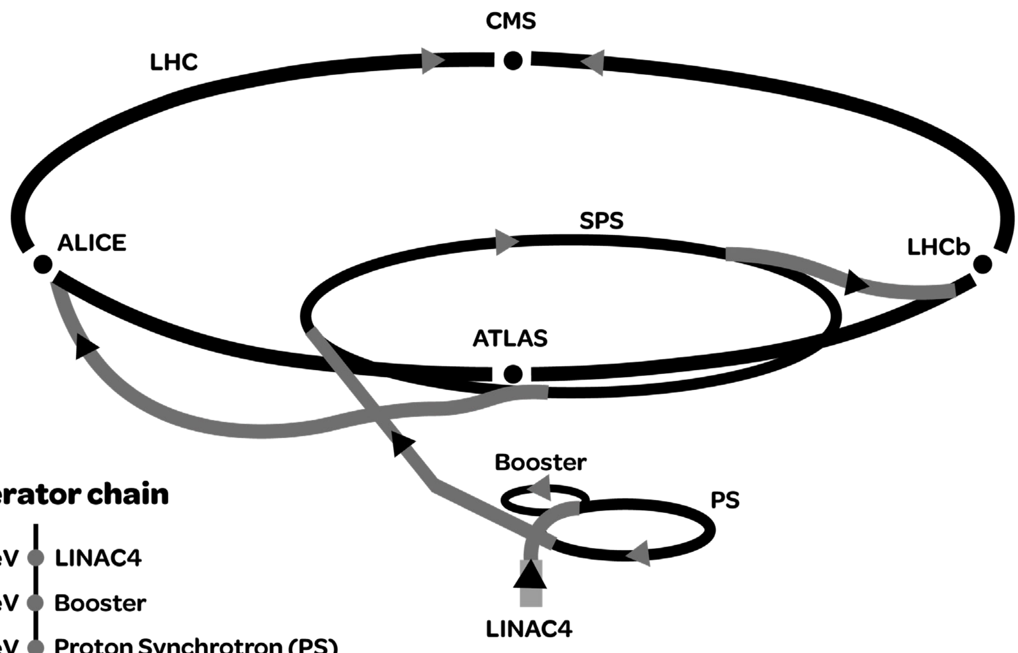
All particle accelerators usually have:

- A source that generates electrically charged particles;
- An electric field to accelerate the particles;
- A magnetic field to control the paths of the particles.

The LHC has the **shape of a circle**, meaning that the particles repeat the same circuit for as long as necessary, getting an energy boost at each turn.

Inside the LHC, the particle beams travel through **vacuum pipes** - containers with as little residual air as possible - to avoid unwanted collisions with air molecules. Beams can be made of different kinds of particles; the LHC uses mainly proton beams and sometimes nuclei of heavy atoms!

After accelerating and smashing particles together, physicists detect and study the results of these collisions. Particle experiments are the **enormous microscopes** that detect the results of these collisions through the traces they leave behind.



Accelerator chain

160 MeV	LINAC4
1.4 GeV	Booster
25 GeV	Proton Synchrotron (PS)
450 GeV	Super Proton Synchrotron (SPS)
6.5 TeV	Large Hadron Collider (LHC)

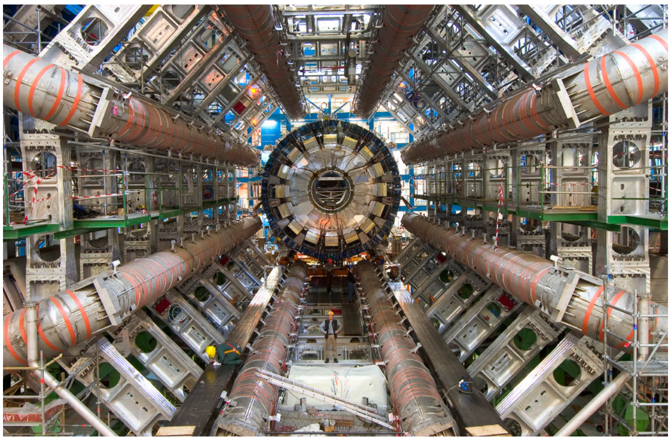
How do experiments at the Large Hadron Collider work?

The Large Hadron Collider (LHC) **accelerates two sets of particles to almost the speed of light** (travelling in opposite directions), before setting them on a path to collide with each other. When they are smashed together, new particles are created, which can be detected and studied by experiments.

ATLAS is the largest experiment on the LHC, and like most particle-physics detectors, it **is made of different layers**. Each of these layers play a unique role and is optimised for different particles - for example, tracking detectors are designed to trace the paths of electrically charged particles.

The ATLAS experiment **sees up to 1.7 billion collisions every second** and only a fraction of them can be recorded and stored.
To make sure only the most interesting collisions are recorded, ATLAS uses super fast electronics and a special selection system.

This decision-making process needs to be near-instantaneous and all the massive amounts of data quickly stored. **ATLAS records over 10,000 TB of data per year** – that's equivalent to 320,000 hours of 4K streaming!



Additional resources

- Kids interested in learning more about ATLAS and the LHC should explore the ATLAS Colouring Book and Fact Sheets (available here: atlas.cern/resources).

- Other resources about the LHC:
    - https://home.cern/science/experiments
    - https://www.youtube.com/watch?v=BEnaEMMAO_s&ab_channel=OxfordSparks
    - https://atlas.cern/resources/cheat-sheets

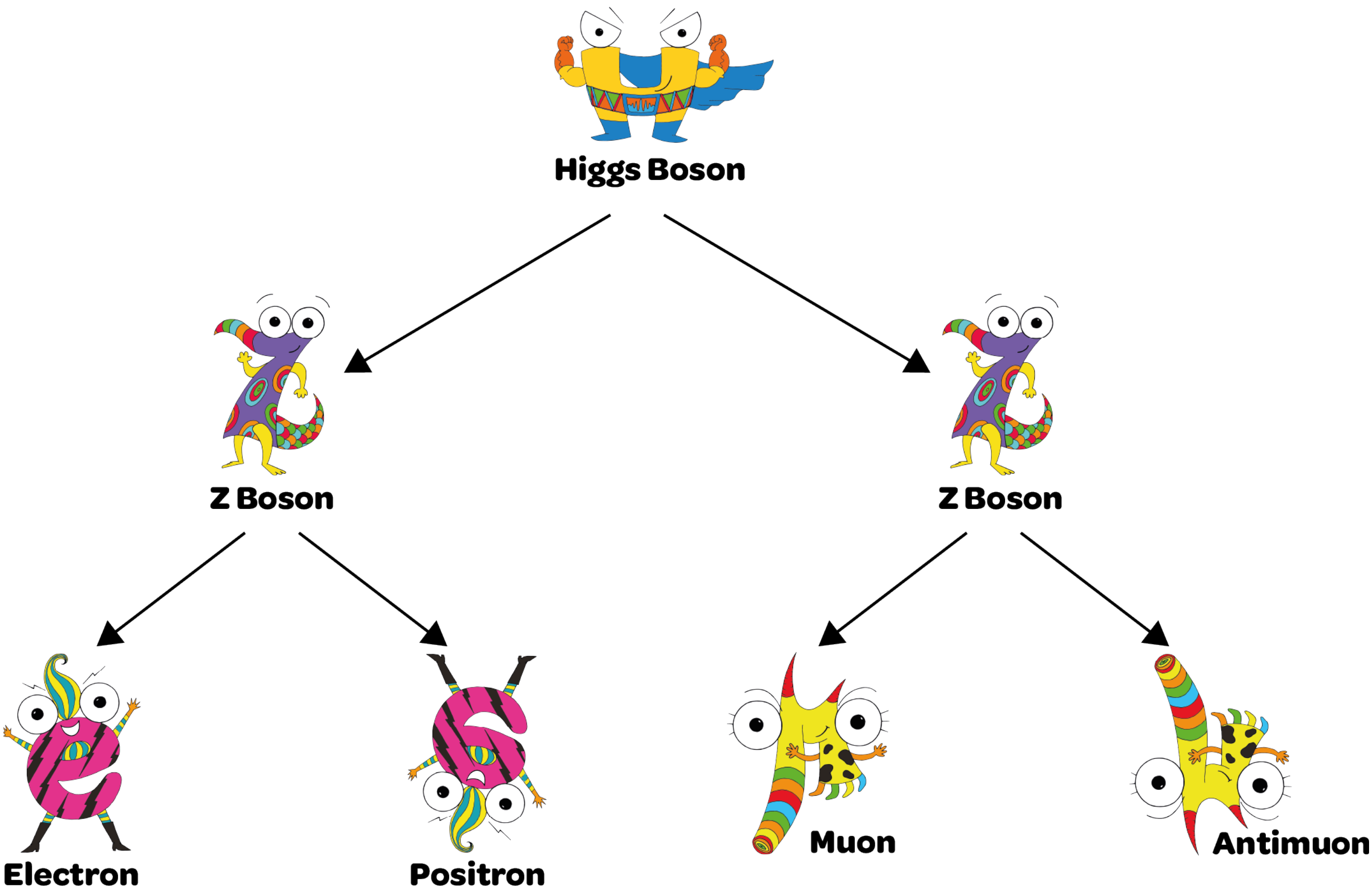
What are particle decays?

When particles transform into multiple other particles, we call it a "particle decay". Particle decays are **mediated by fundamental forces**.

Most of the interesting and relevant particles created in LHC collisions decay into other particles before they can be detected. The only way that physicists can study the properties of such particles is by **measuring their decay products**.

A particle **can decay in multiple different ways** - and each of these has an associated probability.

Find below an example of a particle decay where a Higgs boson decays into two Z bosons. These Z bosons then decay into two electrons and two muons, respectively. These decays are commonly studied at the ATLAS experiment.



Additional resources

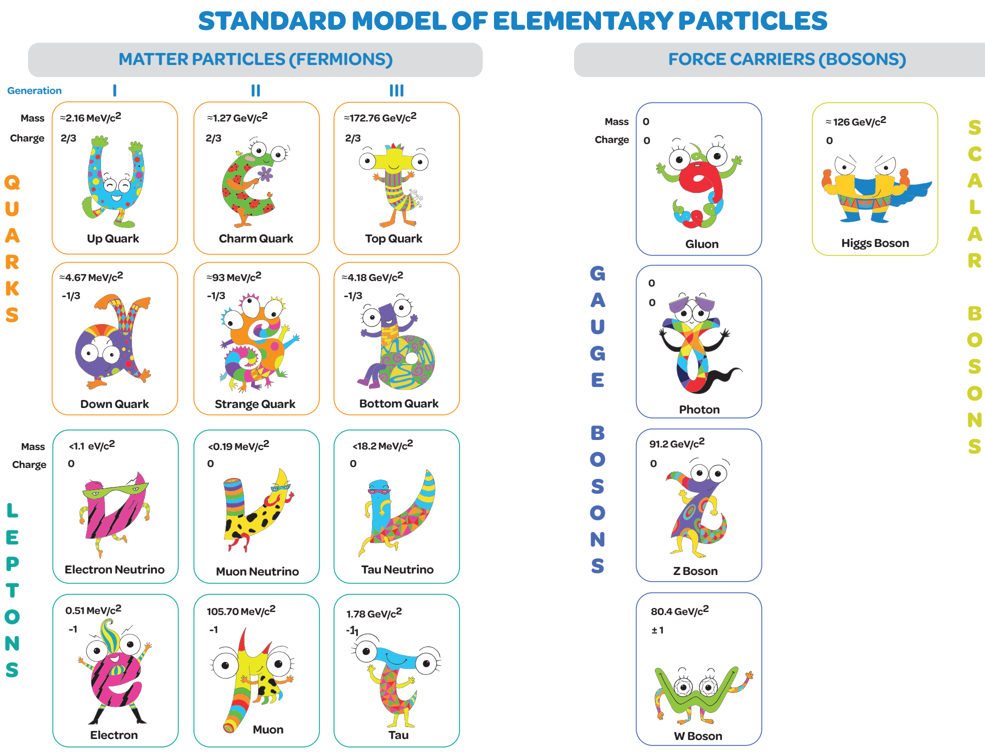
- Activity sheet about particle decays available at atlas.cern/colouring-books

What is the Standard Model of particle physics?

The Standard Model is the result of many decades of research and **summarises the current knowledge** scientists have on the fundamental forces and constituents of matter.

The Standard Model **describes all elementary particles physicists have found so far**! Particles are grouped into matter particles (quarks and leptons) and force-carrying particles (bosons). Both quarks and leptons exist in three distinct sets, called families or generations.

The Standard Model has been in development for quite some time. Even though the Standard Model is incomplete, it does an outstanding job at describing the known Universe. **Physicists are constantly testing the limits of the Standard Model**, looking for new data to prove or refute it.



Additional resources

- Kids interested in learning more about the Standard Model should explore the ATLAS Colouring Book, Standard Model Activity Sheet and Standard Model Cheat Sheet (available here: atlas.cern/resources).

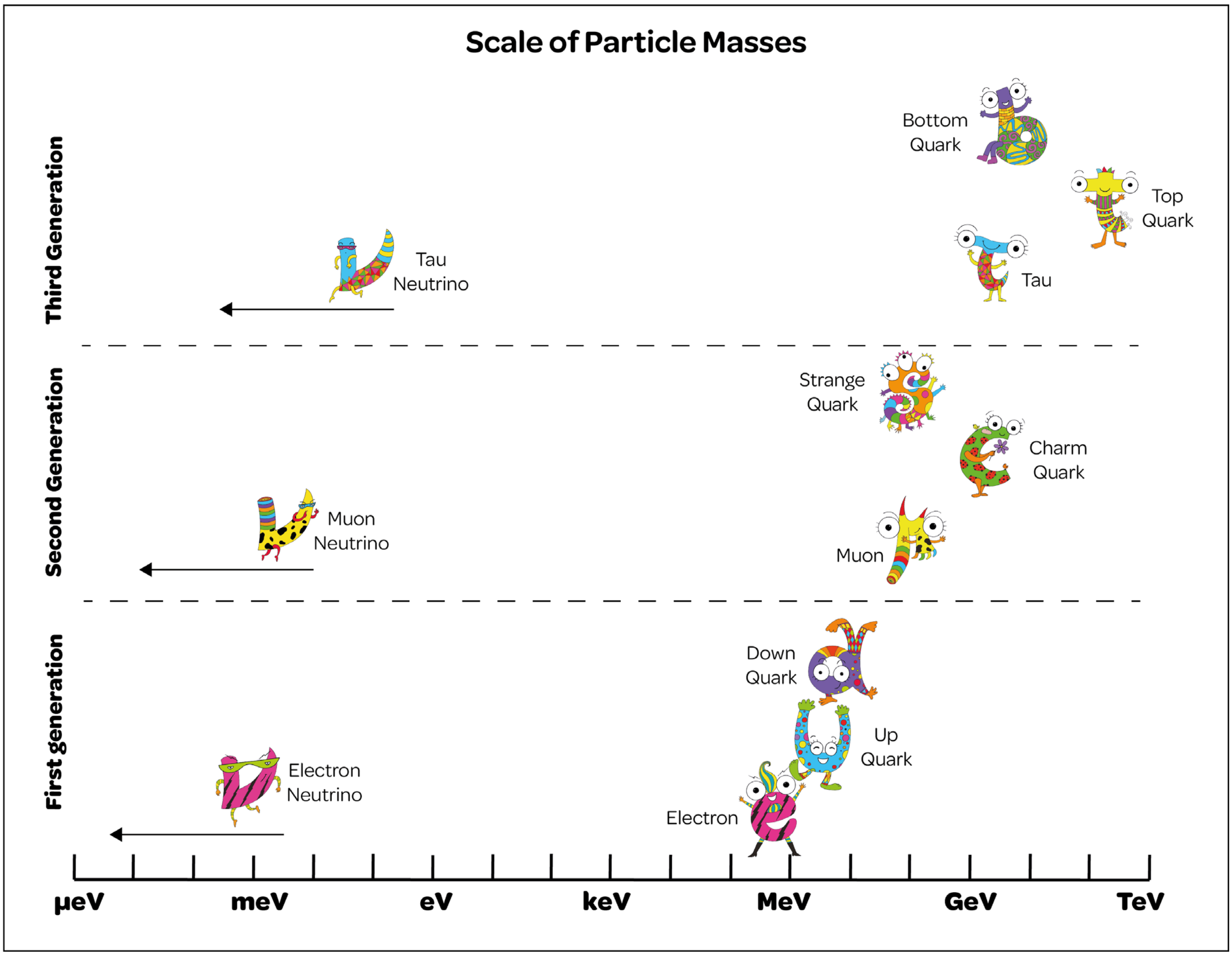
What about particle mass?

Weight is the measure of the force of gravity on an object. Mass is a measurement of how much matter is in an object. The **mass of an object will never change**, but the weight of an item can change based on its location.

For example, in outer space you would have a different weight due to gravity being different. However, you will always have the same mass on Earth as you have in outer space!

For very tiny particles mass and energy are equivalent! **Particle mass is expressed in eV/c^2**, where "eV" represents energy (in electronvolts) and "c" is the speed of light. The **elementary particles we know have very different masses** that can span several orders of magnitude. For example, neutrinos have really small masses, just a few eV, while others have high masses, on the order of 1,000,000,000 eV (1 GeV). Most elementary particles have masses on the order of 1,000,000 eV (1 MeV). The heaviest elementary particle is the top quark, that is as massive as an atom of gold (that has 197 nucleons).

Find below, for each generation of particles, a scale with particle masses.



Logarithmic scale of particle masses.

What are particle generations?

Quarks and leptons are organised into generations. Each generation consists of a pair of a so-called up-type and a down-type quark (electric charges +2/3 and -1/3) and a pair of a neutral and a charged lepton (electric charges 0 and -1). The generations are organised by increasing mass.

All visible matter in the Universe is made from the first generation of matter particles - up quarks, down quarks, and electrons. This is because all second and third generation particles are unstable and **quickly decay** into first-generation particles.

Physicists don't know why there are three generations. It could be possible to have more, who knows!

Additional resources

- Kids interested in learning more about particle generations should explore the Colouring Books and Standard Model Activity Sheet (available here: atlas.cern/resources).

First Generation

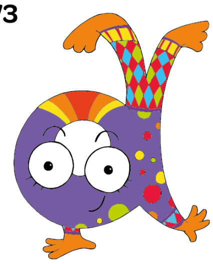
Mass **≈2.16 MeV/c^2**

Charge **2/3**

Up Quark

≈4.67 MeV/c^2

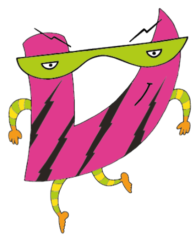
-1/3



Down Quark

<1.1 eV/c^2

0



Electron Neutrino

0.51 MeV/c^2

-1

Electron

What is colour charge?

Elementary particles are further organised following other properties, like electric charge.

A property that is not as well-known outside particle physics is **colour charge**. There are three so-called colour charges: red, green, and blue; although there is no connection between the colour charge of quarks and gluons and the regular colours we know, it is just a name.

Each quark carries a single colour charge, while gluons carry both a colour and an anticolour charge!

Protons and neutrons contain three quarks, each with one of three possible values of colour (red, blue, and green), turning protons and neutrons into a "colourless" object.

What about antiparticles?

For every type of matter particle we've found, there also exists a corresponding antimatter particle, or **antiparticle**.

Antiparticles look and behave just like their corresponding matter particles, except **they have opposite charges**. When a particle and their antiparticle meet, they annihilate each other and create energy.

When the Universe was formed after the Big Bang, matter and antimatter were produced in equal amounts. However, from what scientists have observed so far, our Universe is made only of matter. Why is this? Could antiparticles have other properties that lead to their disappearance? The LHC could help to provide an answer.

Antiparticles can be created in particle interactions, such as those in particle accelerators like the LHC or in the Earth's atmosphere by cosmic rays (see page 12).

Mass	**0.5 MeV/c^2**	**0.5 MeV/c^2**
Charge	**-1**	**1**
		
	Electron	**Positron**

Antiparticles also have many uses in medicine! For example, a special kind of scanner called the PET (Positron Emission Tomography) uses positrons – the antiparticles of electrons – to look into the human body.

During a PET scan, patients are injected with a tracer that produces positrons inside the body. When positrons bump into nearby electrons, they create a pair of photons that can be detected by the PET scanner. As the tracer collects in areas of high metabolic activity, the scan image can help doctors pinpoint areas of interest.

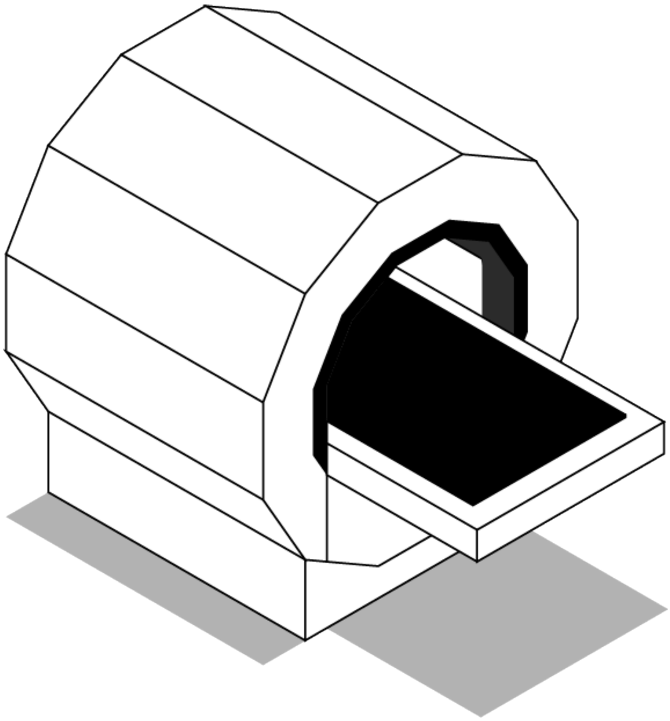


Illustration of a PET scan machine.

Additional resources

- Kids interest in learning more about antiparticles should explore the ATLAS Activity Sheets (available here: atlas.cern/resources).

What are cosmic rays?

Cosmic Rays are **high-energy subatomic particles** that originate from outer space, mostly from supernovas and distant galaxies. Upon reaching the Earth, most cosmic rays are deflected by its magnetic field while the rest interact with the atmosphere and decay. Some of the products of these decays reach the Earth's surface.

Cosmic rays are mainly high-energy protons. They collide with the nuclei of atoms in the Earth's upper atmosphere – like oxygen and nitrogen – creating more particles. Most of these particles then decay and are stopped in the atmosphere before reaching the Earth's surface, with some exceptions like **cosmic-ray muons**.

Muons do not interact strongly with matter, hence those produced in the atmosphere can penetrate even deep into the ground (and be **measured by experiments like ATLAS**).

The rate of cosmic-ray muons arriving at the surface of the Earth is such that about **25 pass through your hand each minute**! Cosmic rays constantly rain down on Earth but by the time they reach us it becomes difficult to trace where they have come from.

Cosmic rays and their interactions with the earth's atmosphere can be considered Nature's LHC. By using particle accelerators, **physicists can mimic the cosmic ray collisions in the lab**, though at much lower energies. But even though accelerators came to provide the best hunting ground for new particles, the physics of cosmic rays is still widely studied.

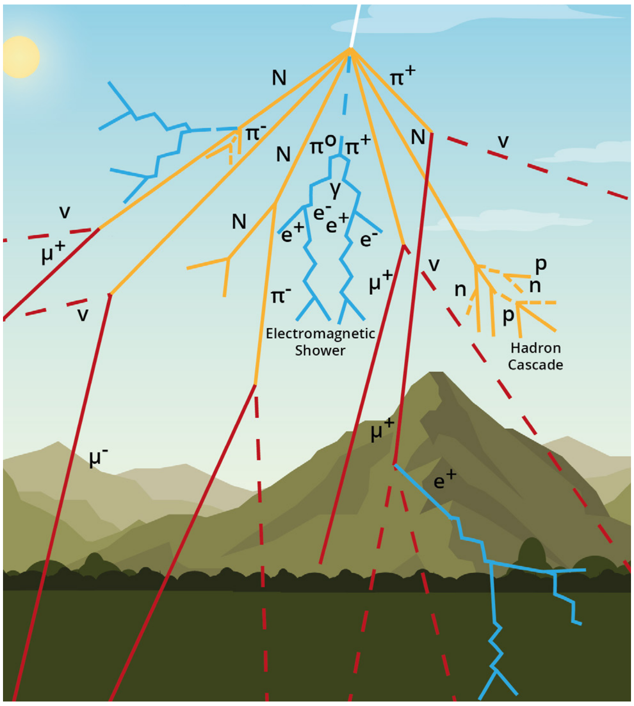


Illustration of the cosmic rays interacting with the Earth's atmosphere.

What about gravity?

While in the colouring books you read about the fundamental forces that operate between fundamental particles, you may have noticed that one is missing: gravity. Why is it not in the book? Well, that's because **we cannot describe it at very small scales**!

Gravity is a **force of attraction** that acts between everything with mass. On Earth, the gravitational force is what pulls everything towards the ground. It is responsible for the formation of stars and galaxies. It has influenced the way that the Universe has evolved since its origin in the Big Bang.

As elementary particles have mass, they are also affected by gravity. Scientists are working on understanding how gravity can fit inside the Standard Model. Like the other forces, it is hypothesised that the gravitational force could be carried by a suitable messenger particle: the **graviton**! Will scientists find it at ATLAS?

Is that all?

We already know that the **Standard Model cannot explain everything** we observe in the Universe. For example, how does gravity fit in it? What is dark matter and what happened to antimatter?

Scientists have come up with a lot of **different explanations for these unresolved mysteries** that go beyond the Standard Model. There could be new particles, forces, states of matter, or particle-like phenomena – all of which may be discovered by ATLAS.

Some new theories – like **Supersymmetry** – extend the mathematical framework of the Standard Model. Supersymmetry doubles the number of fundamental particles, stating that each particle of the Standard Model has a supersymmetric "partner" particle.

Searches by ATLAS physicists can target specific theories – for example, looking for a supersymmetric top quark – or can look broadly for evidence of **new phenomena** – for example, looking into particle decay products to see if there is a non-Standard Model particle that decayed into Standard Model particles.

How can I work at ATLAS?

Good question! Your starting point should be: go out and explore, always be curious about what surrounds you. **An inquiring mind is key to being a scientist**.

If you want to become an experimental or theoretical physicist, you should make sure to **study physics at university** at the Bachelor's level. From there, a Masters and Doctorate degree focusing on particle physics will be essential. Once you get to university, you may be able to join the ATLAS Collaboration! Hundreds of institutes worldwide are part of ATLAS, all offering opportunities for students. To learn more, visit: https://atlas.cern/discover/collaboration

But ATLAS and the LHC need more than just physicists! Maybe you would prefer to develop the software that selects the collisions happening inside the ATLAS experiment (computer scientist)? Or maybe you will want to build the particle detectors (mechanical engineer) or design its electronic components (electrical engineer)?

Text and project development by Mariana Velho
Particle illustrations by Carolina DeLuca
Additional illustrations by Mariana Velho

Find more information, activities and games at
https://atlas.cern/resources/teachers

ATLAS EXPERIMENT