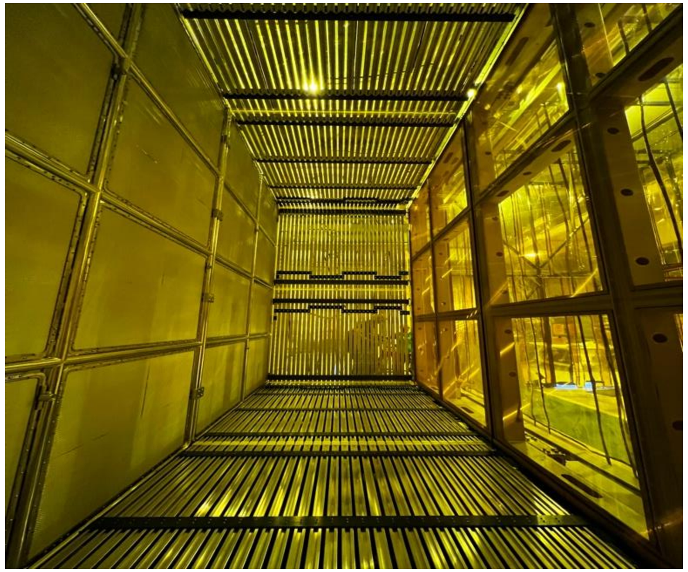
History of Particle Physics

Karan Kumar

Welcome

- Karan Kumar
- 3rd year Graduate Student working in Neutrino Physics
- Bachelor in Physics and Applied Mathematics from Stony Brook University
- Associate Degree in Computer Science from LaGuardia Community College



Class Policy

- Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:00 AM, 5 min break at noon).
- Up to four absences
- Lateness or leaving early counts as half-absence.
- Send email notifications of all absences to shpattendance@columbia.edu

Class Policy

- No cell phone uses during the class
- Feel free to step outside to the hallway in case of emergencies, bathroom, and starvations.
- Feel free to stop me and ask questions / ask for clarifications.

I am presenting these lesson with as little bias as possible. I highly encourage you to take this information, continue researching as you progress in your studies, and form your own informed opinions.

Survey

- What do you know about Particle Physics?

Survey

- What do you know about Particle Physics?

- What is matter made of?

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Throughout history, scientists have often claimed to have discovered the fundamental particles of nature, only for the next generation to prove them wrong. Time will tell whether the particles we call fundamental today are truly the fundamental particles.

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In this lecture, we will study the history of particle physics.

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What scientists mean by “empty” is very different from what you might think. At the smallest scales, space isn’t really empty at all. It is full of tiny jitters, with particles briefly appearing and disappearing. We will learn more about this later.

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- This is very different from our everyday experience where matter seems continuous.
- What looks solid and continuous to us is, at the tiniest scales, mostly empty space.
- Even more remarkable, these building blocks come in only a handful of types such as quarks, electrons, neutrinos, and a few others, yet together they give rise to everything we see around us.

Discussion Time [1 min]

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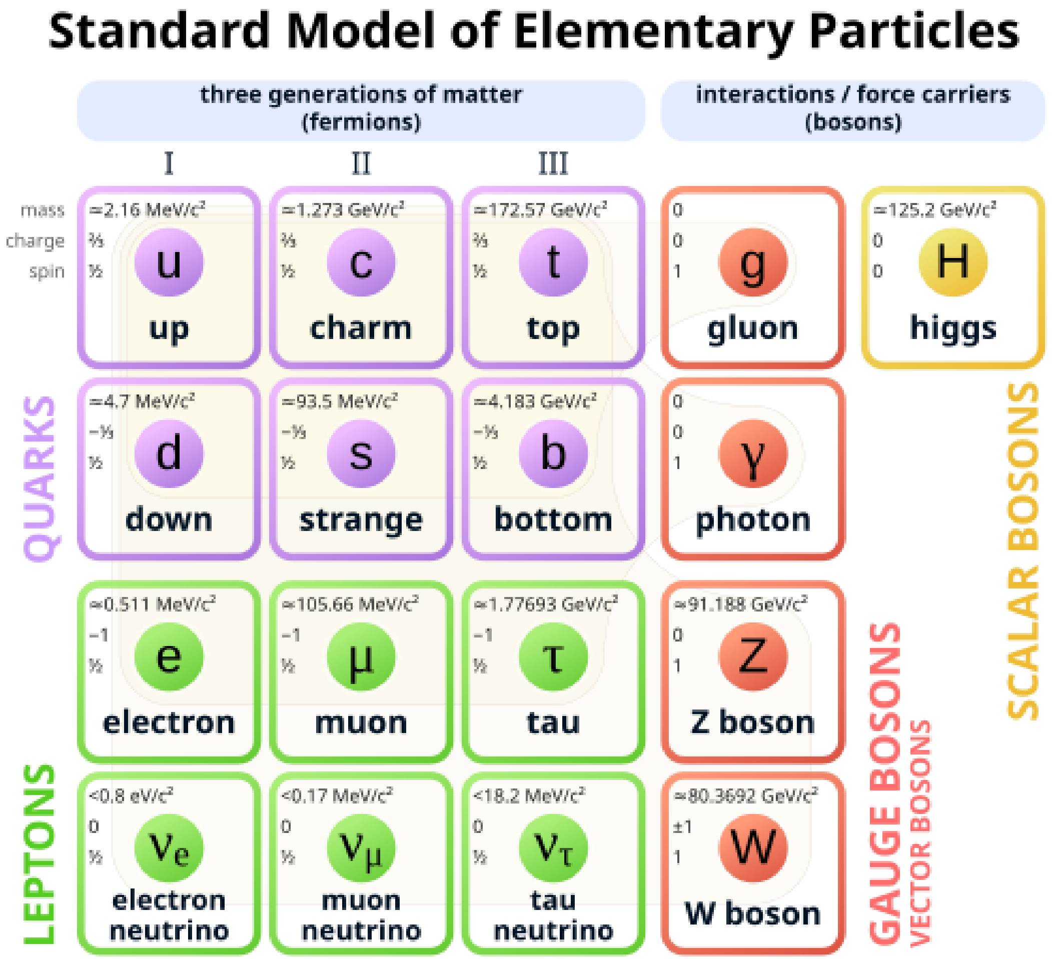
- **Quantum mechanics assumes this:**
  The math of quantum mechanics treats swapping two electrons as leaving the system unchanged, but it doesn't explain *why* they are identical.
- **Quantum Field Theory (QFT) explains it:**
  QFT says there is a single electron field filling the universe, and electrons are simply excitations (or "ripples") of that field. Since all electrons come from the same field, it's natural that they are indistinguishable.

Discussion Time

- Can you tell the difference between one electron and another?

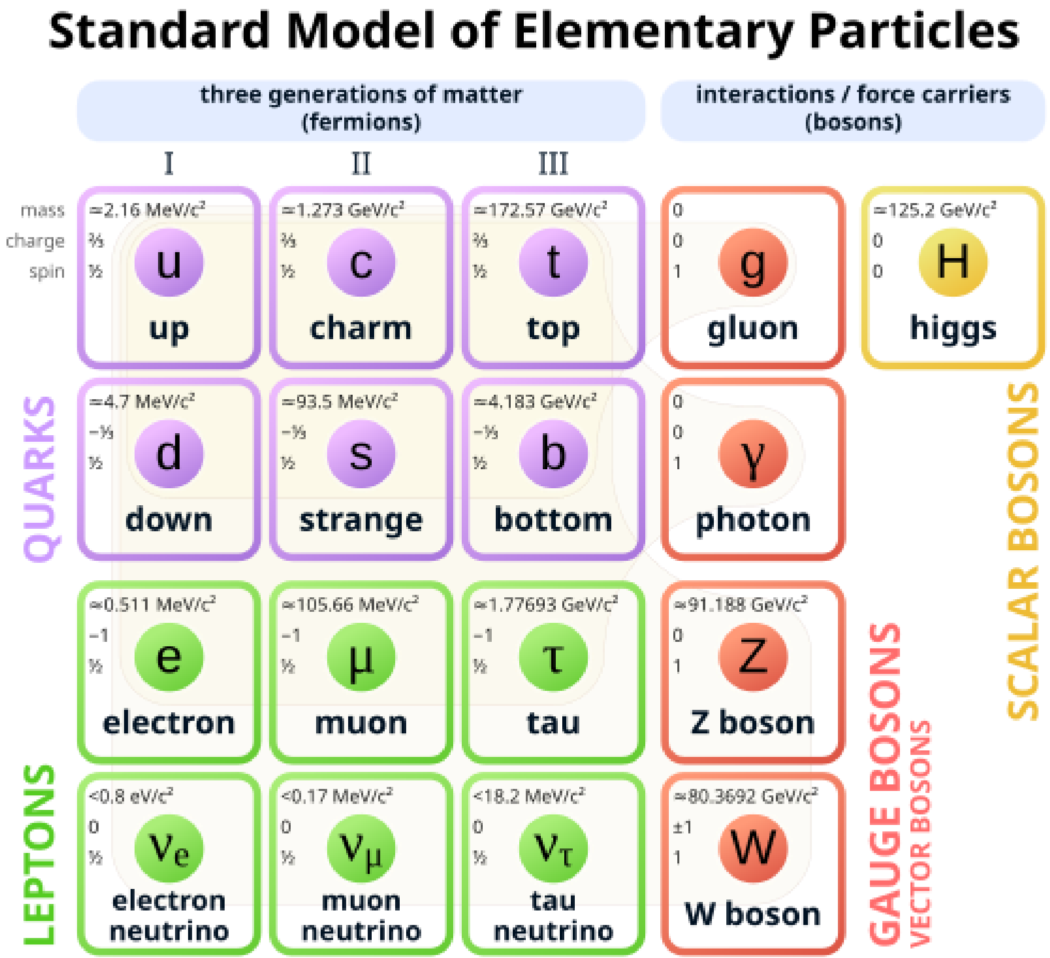
Because particles like electrons are fundamentally indistinguishable, we don’t need to track them one by one. Studying the behavior of one electron tells us how all electrons behave. This lets us write universal laws of physics that apply everywhere.

The Standard Model



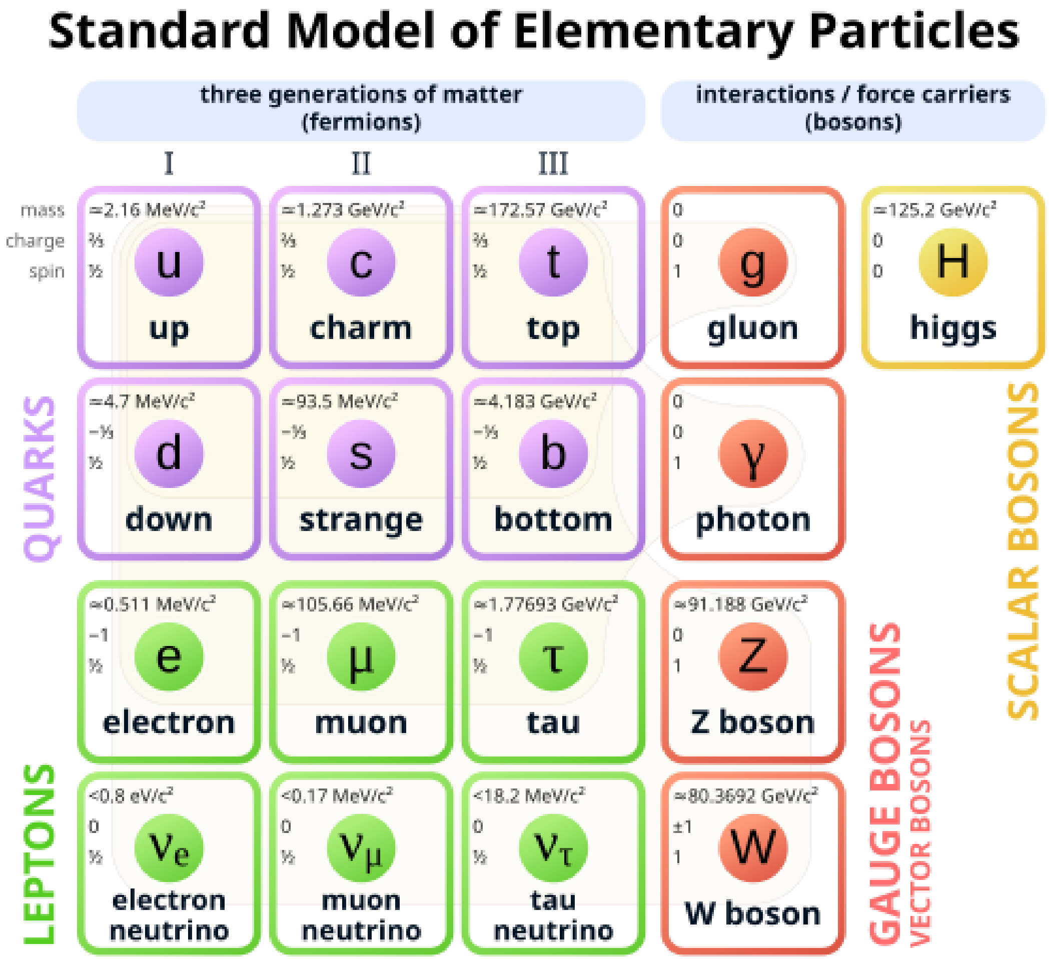
This is the periodic table of particle physics.

The Standard Model



We call it the standard model of elementary particle.

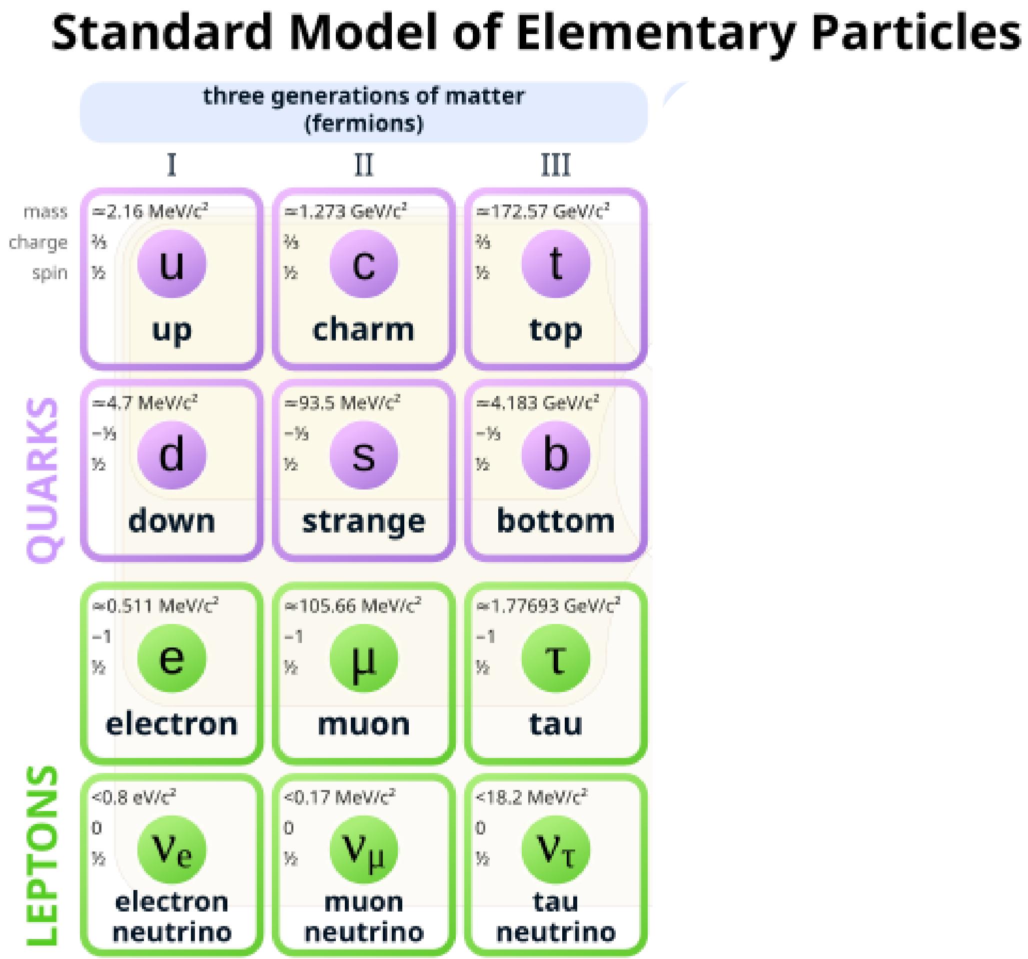
The Standard Model



It contains list of all the elementary particle.

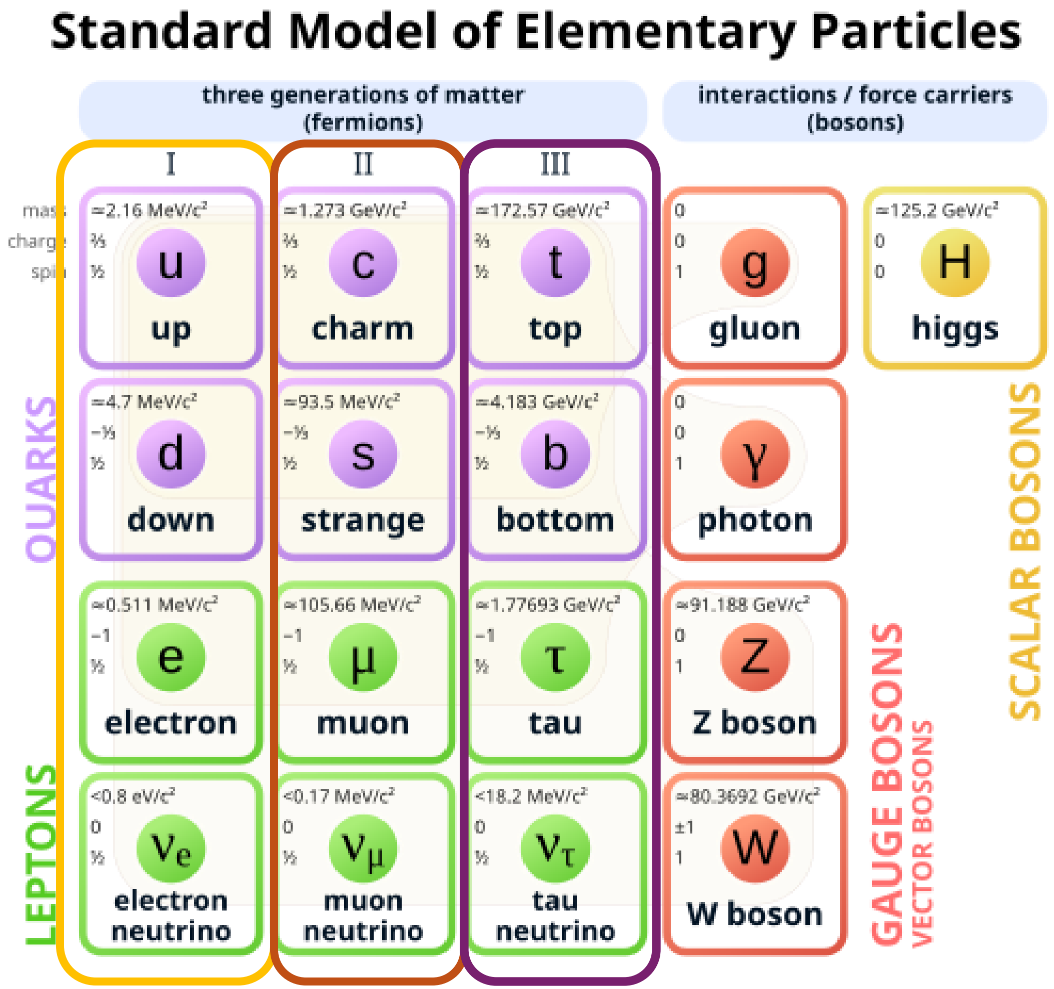
The Standard Model

The Standard Model describes matter as being made of **fermions**, which are the building blocks of everything around us.



The Standard Model

Fermions, the building blocks of matter, come in three generations. Each generation contains two quarks and two leptons.

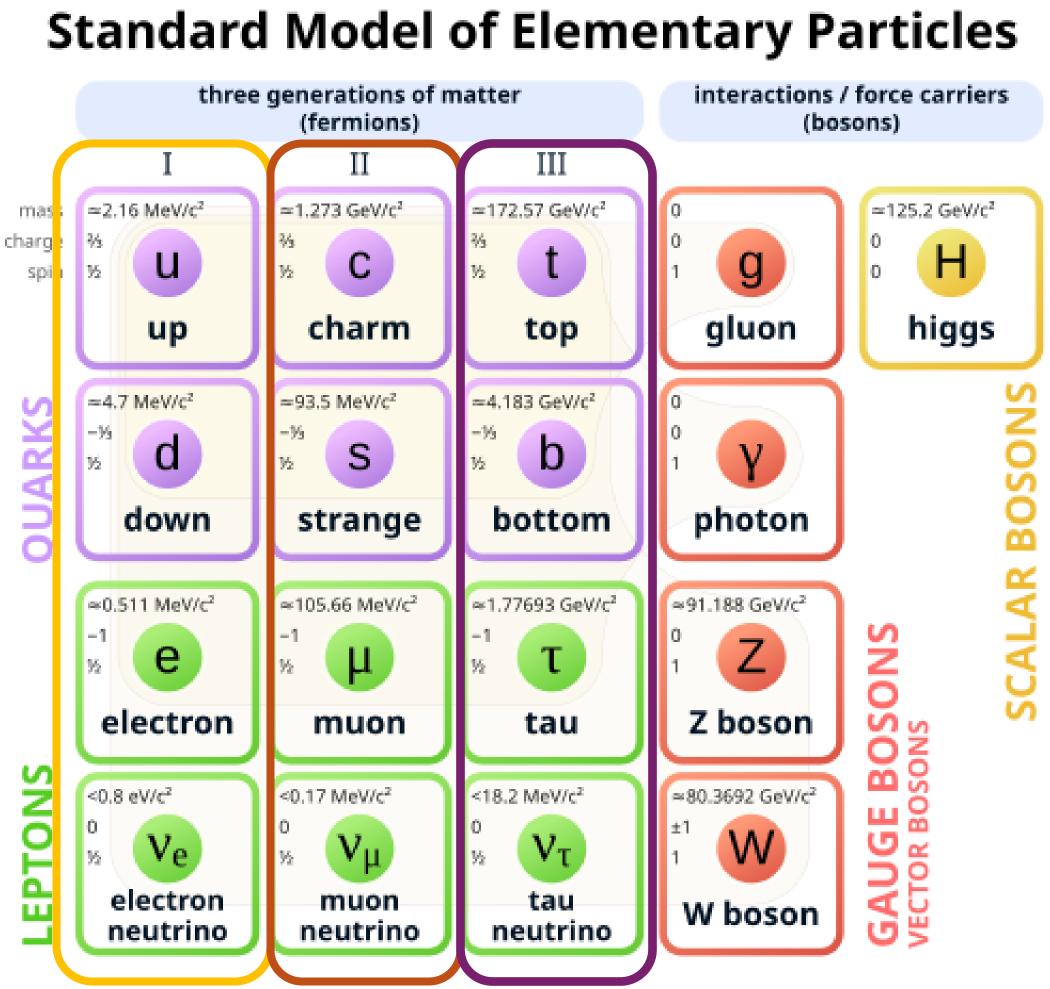


The Standard Model

Fermions, the building blocks of matter, come in three generations. Each generation contains two quarks and two leptons.

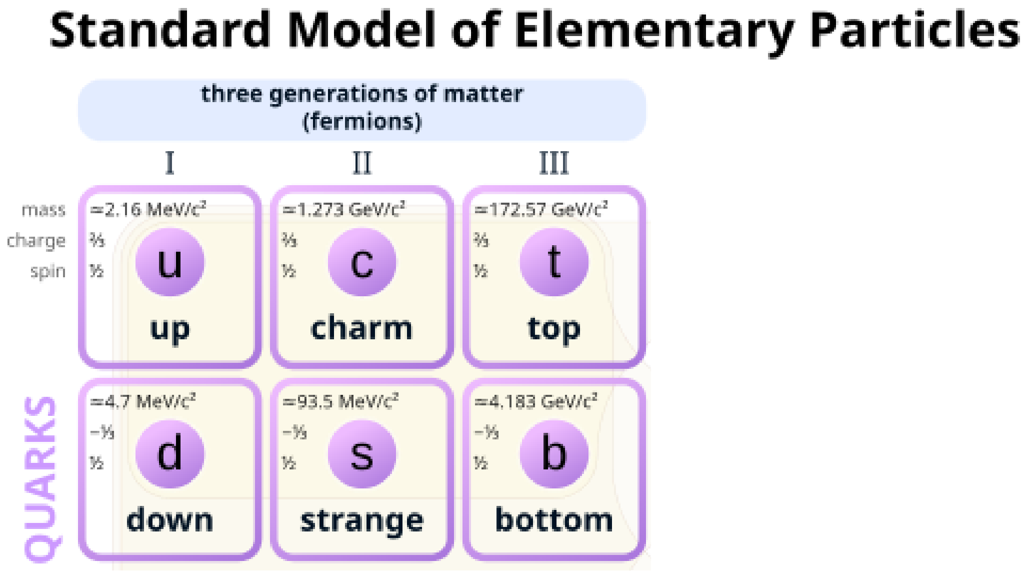
All the matter we see around us is made of the first generation of fermions, yet nature has repeated this pattern two more times. We do not know why.

But Nature loves to repeat.



The Standard Model

Quarks are one of the two families of fermions, and they are the building blocks of protons, neutrons, and many other particles.



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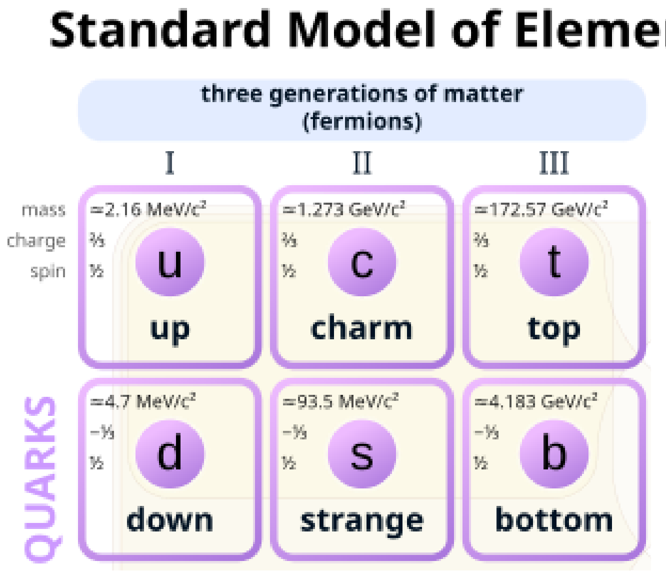
Quarks are one of the two families of fermions, and they are the building blocks of protons, neutrons, and many other particles.

There are six types of quarks, which physicists call "flavors": up, down, charm, strange, top, and bottom.



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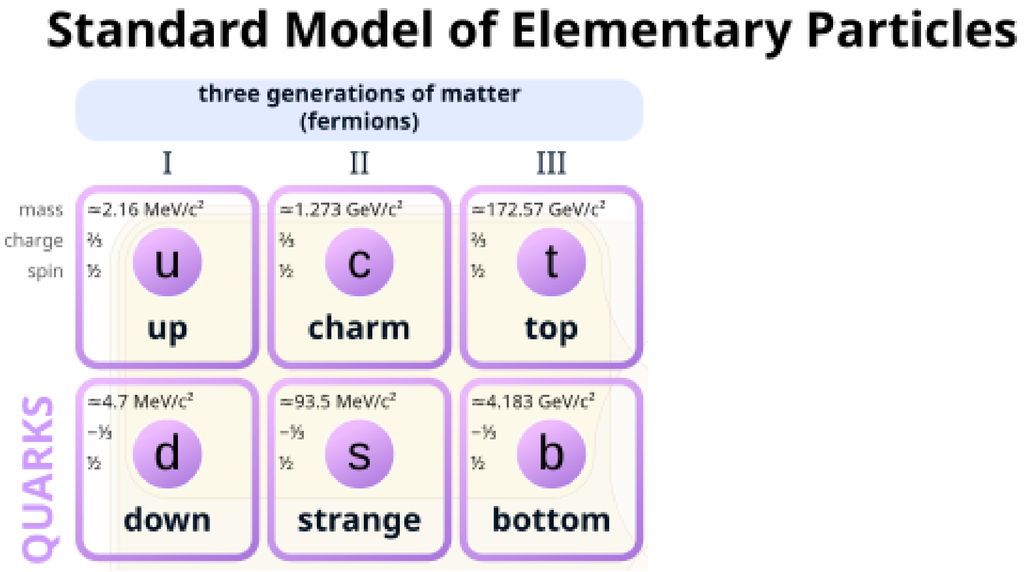
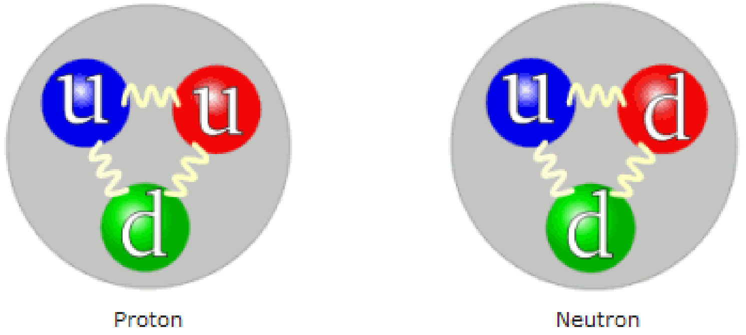
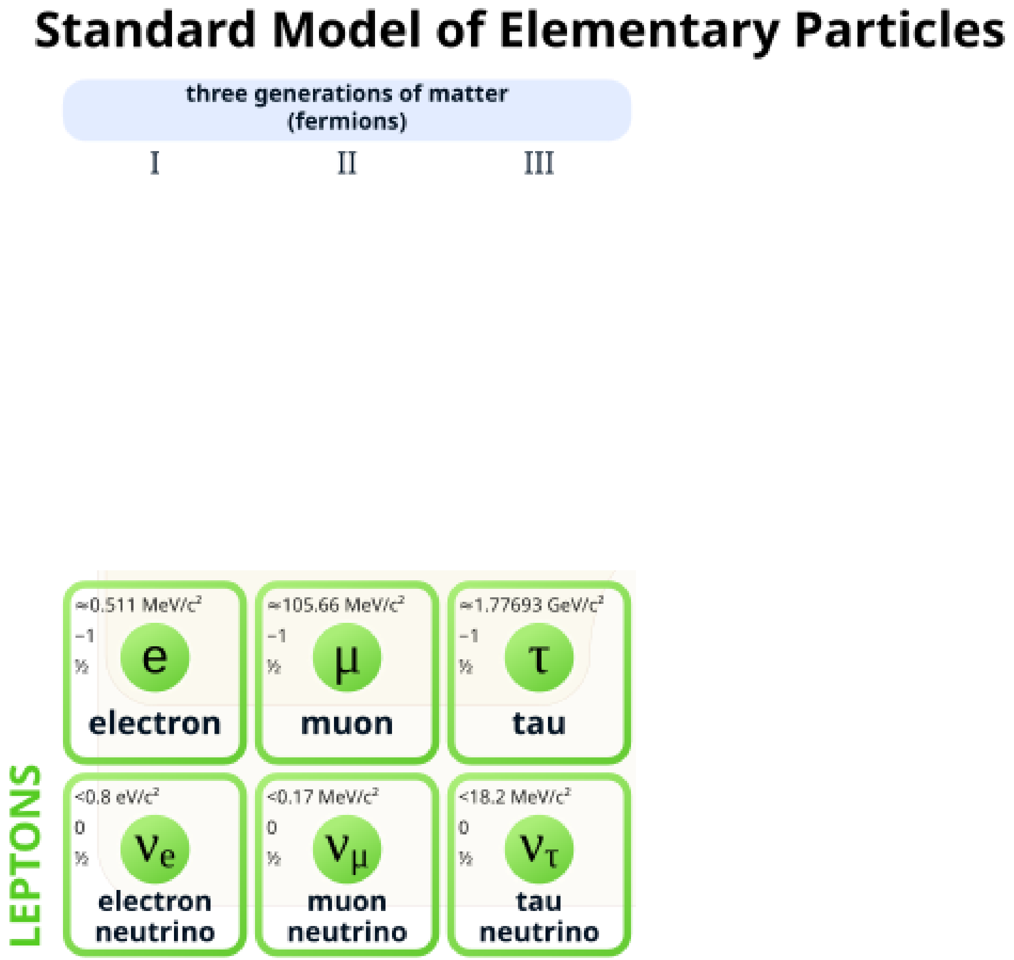




Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

The Standard Model

- Leptons are one of the two families of fermions.



The Standard Model

- Leptons are one of the two families of fermions.

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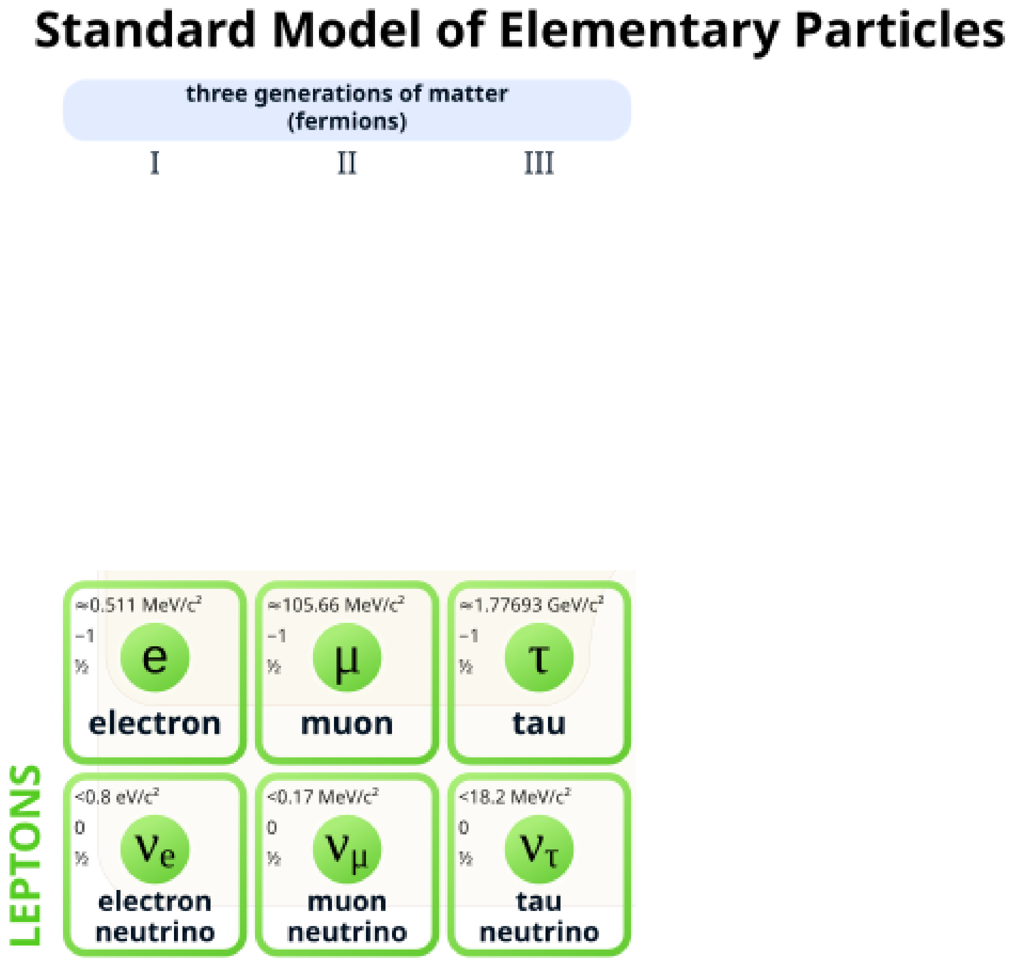

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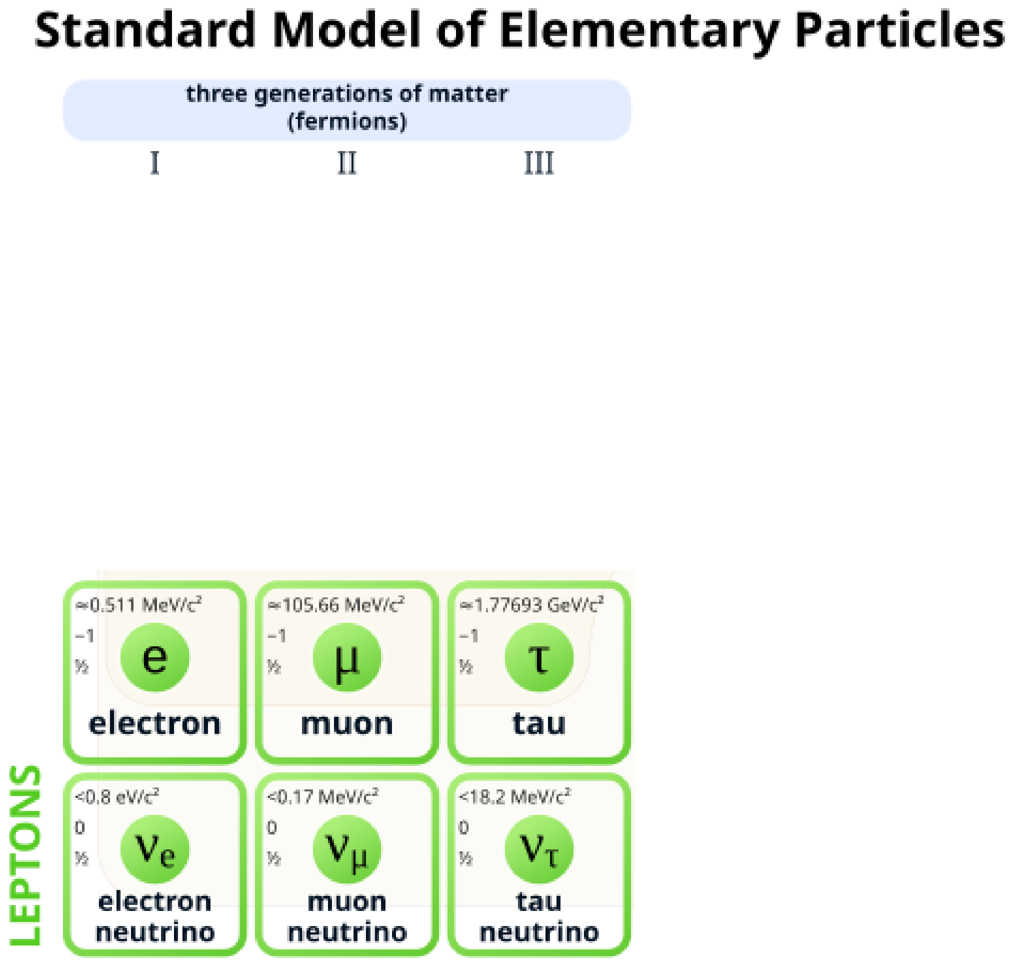
- Electrons are familiar because they form atoms by orbiting nuclei, while muons and taus are heavier versions that are unstable and quickly decay into electrons.



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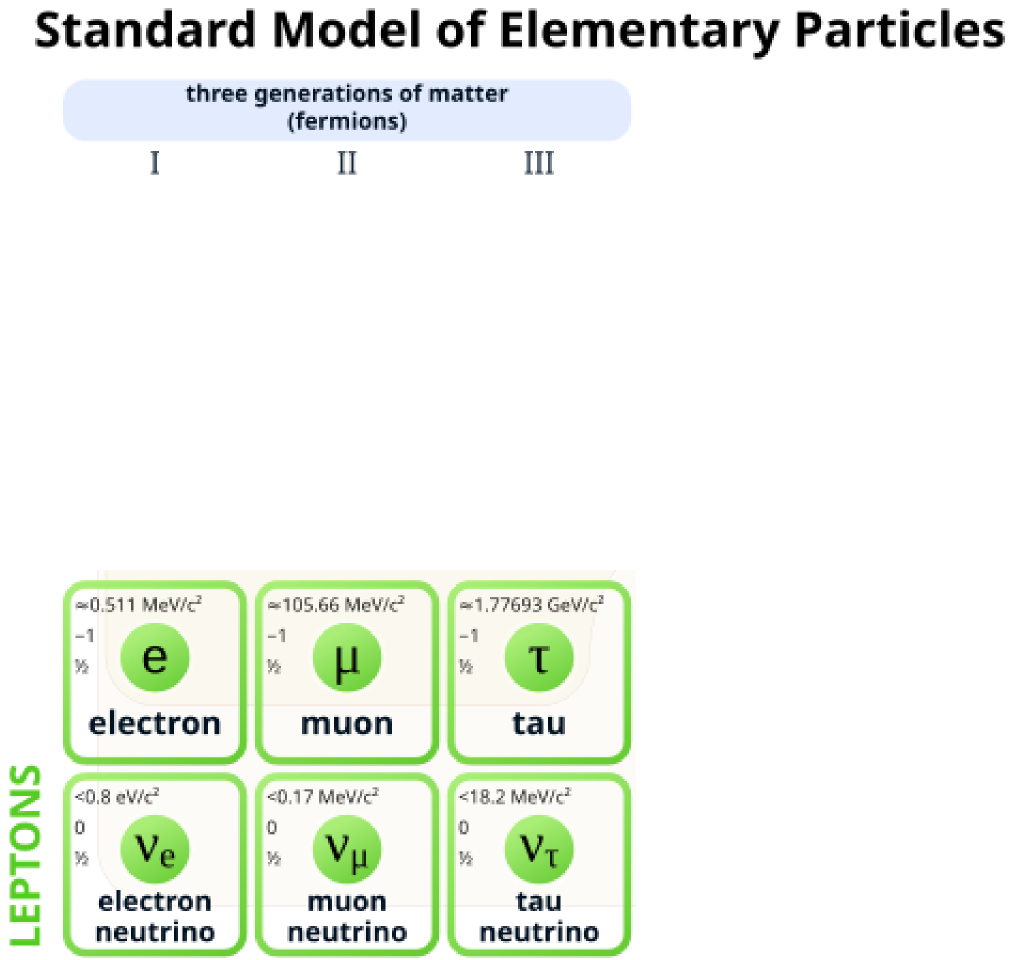
- Electrons are familiar because they form atoms by orbiting nuclei, while muons and taus are heavier versions that are unstable and quickly decay into electrons.
- Neutrinos are extremely light, electrically neutral, and interact very weakly.



Quiz Time

If you had to guess, how many **neutrinos** do you think passing through you right now?

A. Approx. Thousand per second
B. Approx. Million per second
C. Approx. Billion per second
D. Approx. Trillion per second

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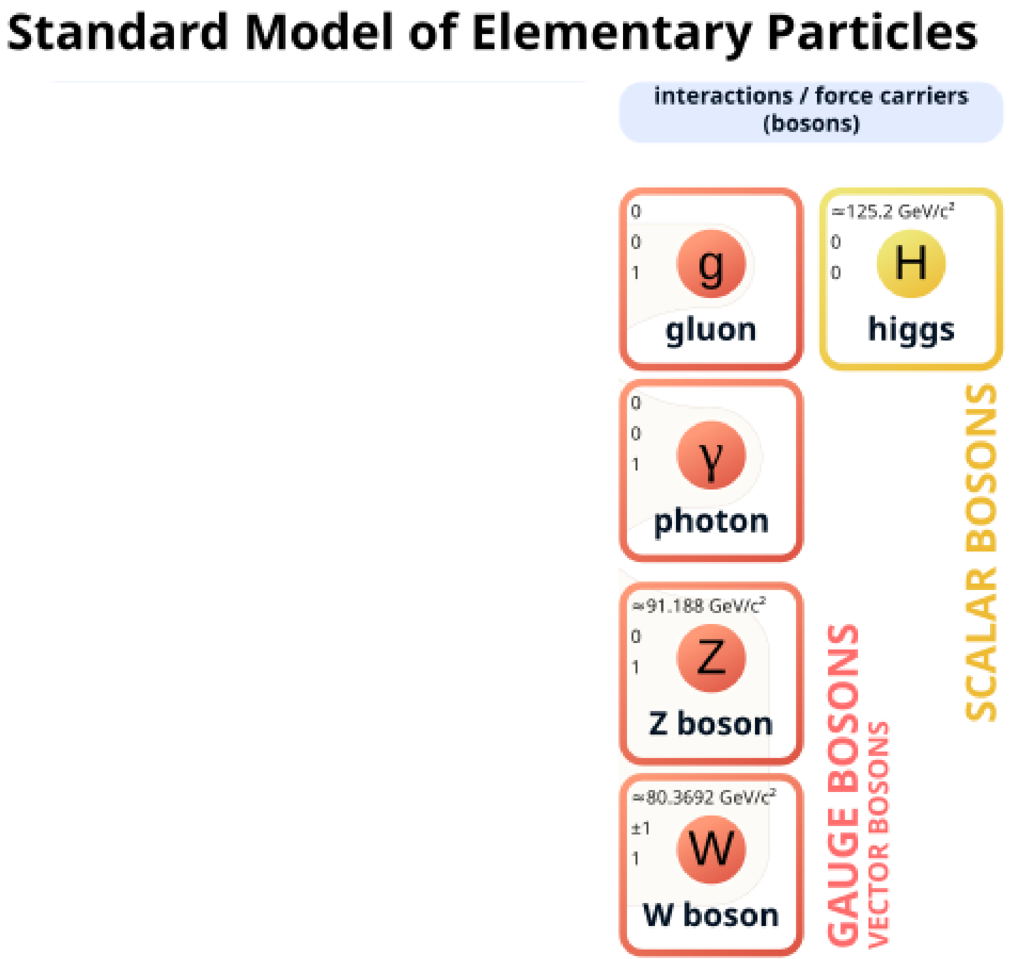
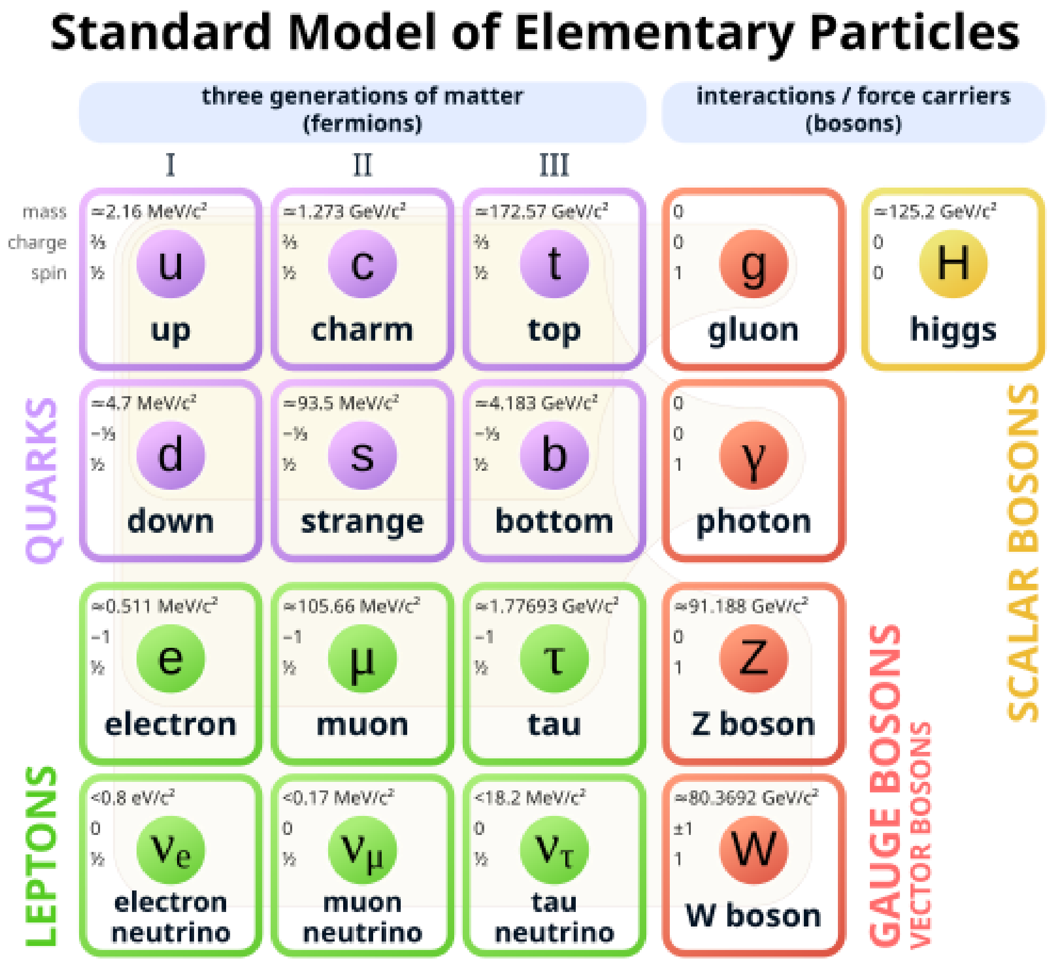
The Standard Model

Bosons are the particles that carry the fundamental forces. They act as messengers between matter particles. We will study them when we discuss about interactions.





How did we get here?

History of Particle Physics

- The Classical Period (1897-1932)

➢ Electron, Proton, Neutrons, Atoms, and Radioactivity

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History of Particle Physics

- The Classical Period (1897-1932)
  - ➢Electron, Proton, Neutrons, Atoms, and Nuclei

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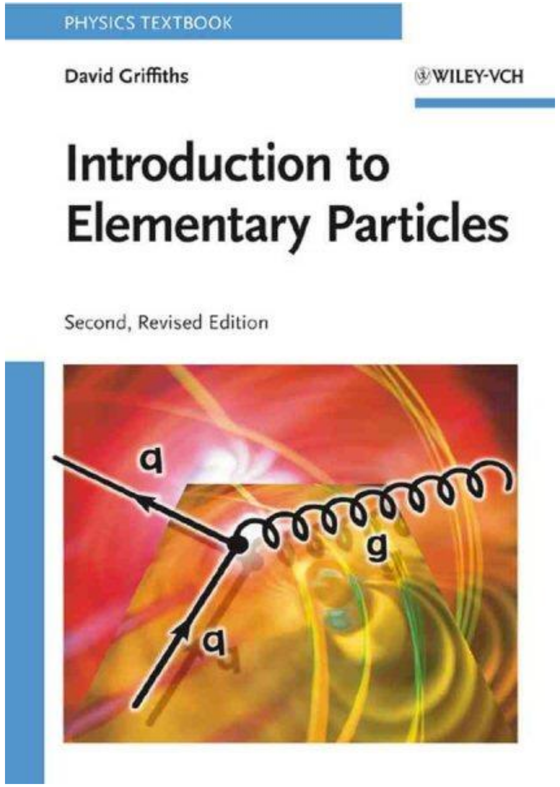
- The Standard Model and Beyond the Standard Model (1978- Present)
  - ➢Higgs Boson, Dark Matter, Right-Handed Neutrinos, Supersymmetric Particles, GUT, String Theory (Theory beyond the Standard Model and have not be confirmed)

Good Reference Book

- Introduction To Elementary Particles by David Griffiths



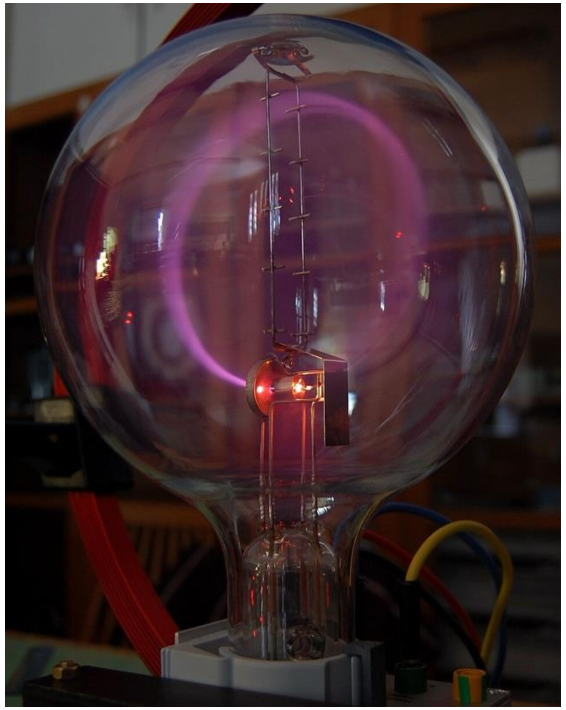
Most of material in these slides are taken from this book. I will present summarized version of historical fact, you can read this book and go into details.

The Classical Period (1897-1932)

Electron, Proton, Neutrons

Discovery of Electron

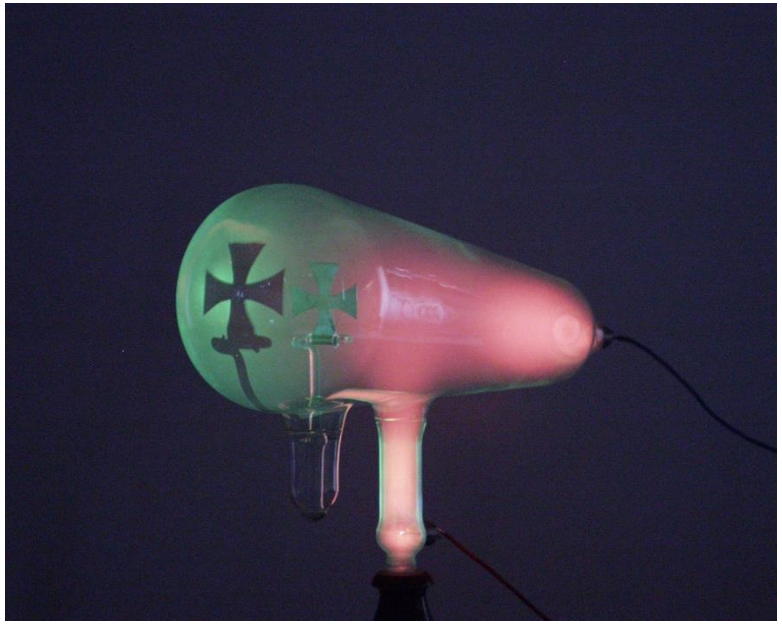
- Toward the end of the 19th century, scientists discovered that hot metal filaments emit "cathode rays," which could light up fluorescent screens.



Source: Wikipedia

Discovery of Electron

- At first, these rays were thought to be a type of invisible radiation, like UV light.



Source: Wikipedia

Discovery of Electron [Quiz]

Question

UV rays are made of photon which don’t have electric charge, if cathode rays were made of photon, what would happen to cathode rays if you put them in electric and magnetic fields?

1. Nothing.
2. Bend.
3. I don’t know.

Discovery of Electron [Quiz]

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1. Nothing.
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Discovery of Electron

But J. J. Thomson observed that cathode rays **do bend** in electric and magnetic fields, which is how he concluded they are made of **charged particles**, not photons.

Source: Wikipedia

Discovery of Electron

- But these charge particle could be ions $(H^{+}, Na^{+}, \mathrm{Cl}^{-}\ etc)$.
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Discovery of Electron

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If they were ions,

1. Ions (like H^+, Na^+, etc.) are thousands of times more massive than electrons.
2. If cathode rays were ions, their e/m ratio would be very small.
3. Thomson measured a **very large e/m**, meaning they must be much, much lighter than even the smallest atom (hydrogen).

Discovery of Electron

If they were ions,

4. If they were ions, using different metals should have produced different ions with different masses.

5. Instead, he always got the same e/m ratio → showing these particles are **universal**.

Discovery of Electron

If they were ions,

6. Positive ions would bend the opposite way in electric/magnetic fields.

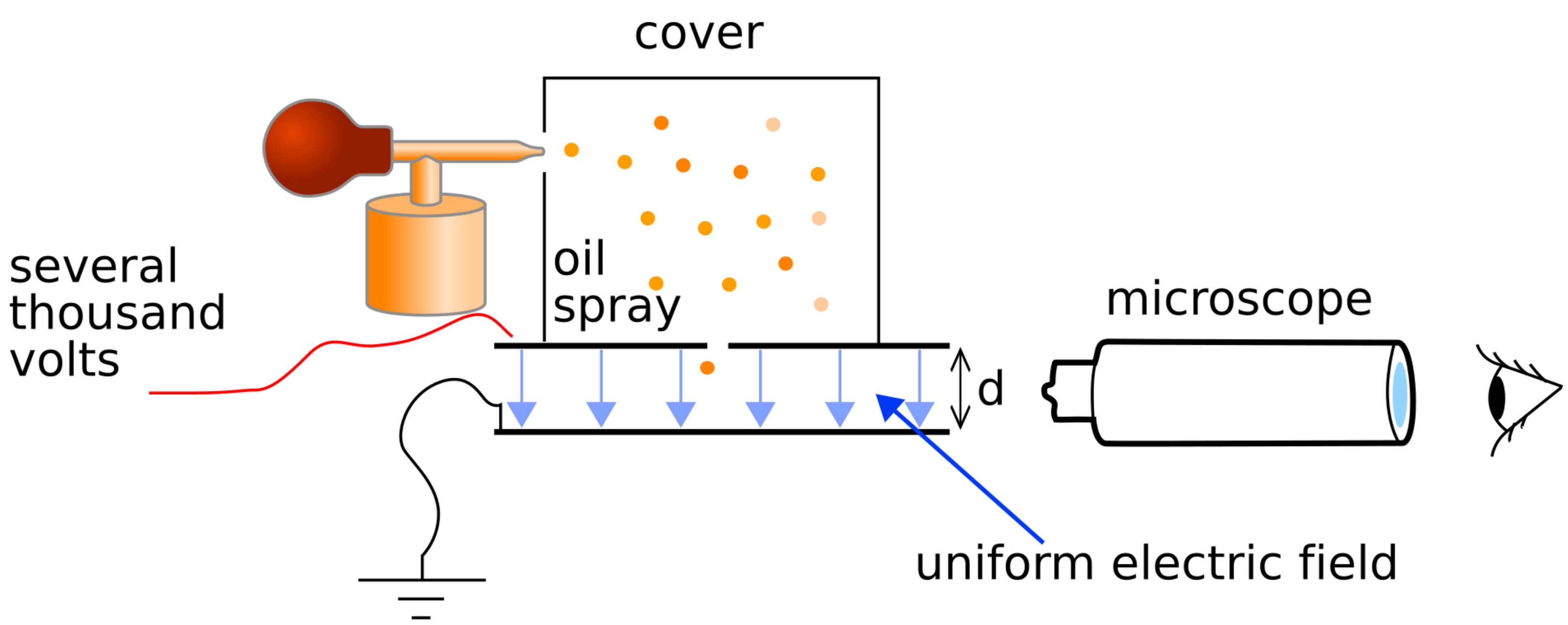
7. Cathode rays always bent the way negative charges should.

Discovery of Electron

These could not be ions. They had to be something more fundamental. We now call these particles electrons.

Oil Drop Experiment

- Millikan's 1909 oil drop experiment measured the **charge of a single electron** by balancing tiny charged oil droplets in an electric field.



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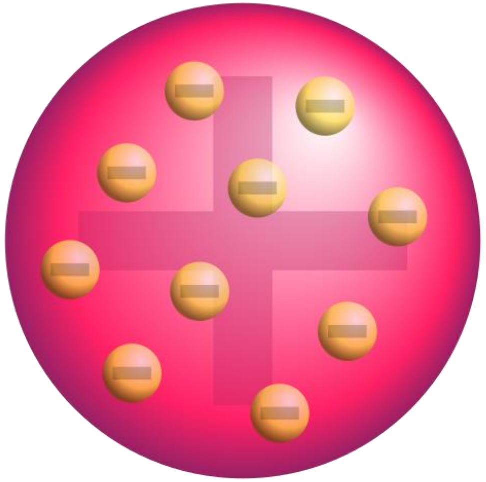
- He found that all droplet charges were multiples of a smallest value e=$1.6 \times 10^{-19}\ C$, proving that electric charge is quantized.
- Combining this with Thomson's e/m result gave the **electron's mass**, $m_e = 9.11 \times 10^{-31} kg$, making it the first subatomic particle with known mass and charge.

Plum Pudding Model

- Thomson proposed that atoms were neutral “plum puddings,” with light, negatively charged electrons embedded in a heavy, positively charged “dough” to balance the charge. But this model was later disproven by Rutherford’s gold foil experiment

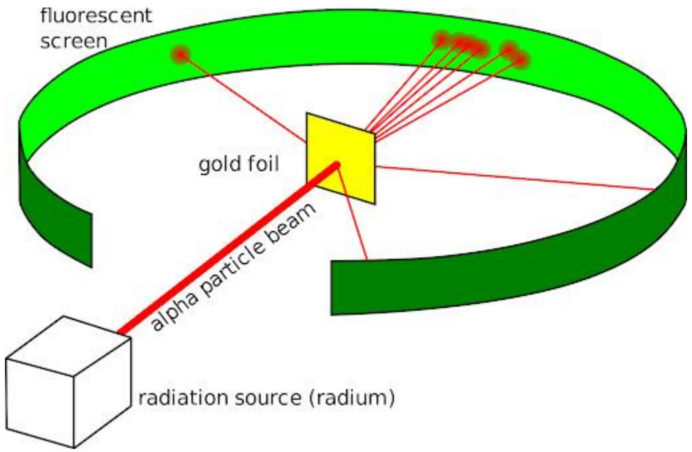


Source: Wikipedia

Rutherford’s Gold Foil Experiment

The Setup

- Rutherford and his team took a very thin sheet of gold foil, only a few atoms thick.
- They shot alpha particles at it, which are small positively charged particles that come from radioactive materials.
- Around the foil, they placed a screen that would flash when an alpha particle hit it, letting them see where the particles went.

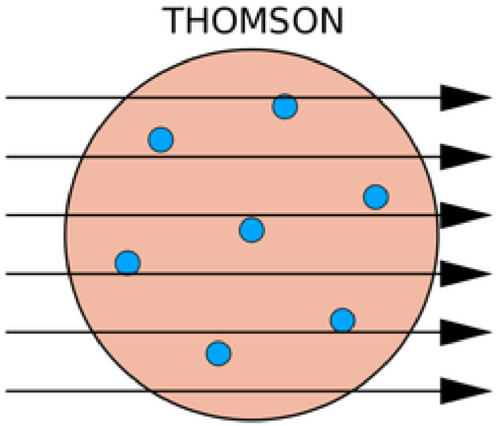


Source: http://large.stanford.edu/courses/2017/ph241/sivulka2/

Rutherford’s Gold Foil Experiment

What They Expected

At the time, scientists thought atoms were like plum pudding. The positive charge was spread out like a cloud, and the tiny electrons were sprinkled inside like raisins. If this idea was right, the alpha particles should have passed straight through the foil, maybe bending just a little.



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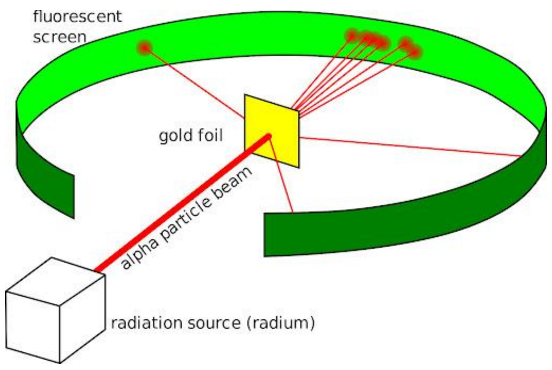
Rutherford’s Gold Foil Experiment

What They Saw

- Most alpha particles did go straight through the foil. But some were deflected at very large angles. A few even bounced almost straight back. This was completely unexpected. Rutherford said it was like firing a cannonball at a piece of tissue paper and having it come back to hit you.



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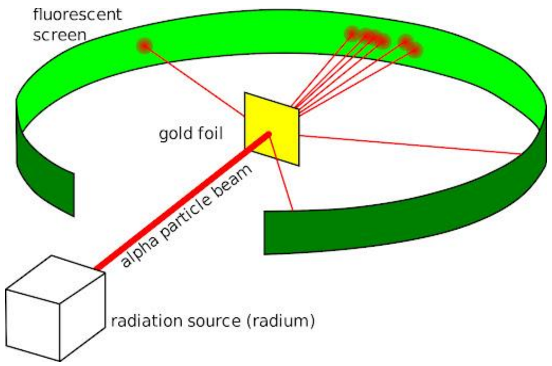
- Alpha particles are very heavy compared to electrons, so nothing in the plum pudding model should have been able to stop them, let alone send them back.



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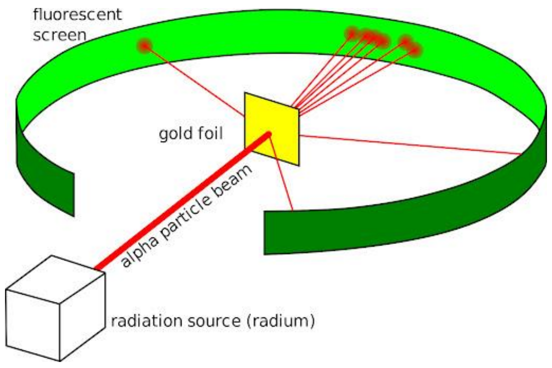
- Alpha particles are very heavy compared to electrons, so nothing in the plum pudding model should have been able to stop them, let alone send them back.
- Rutherford realized this could only happen if almost all of the mass and positive charge of the atom was packed into a very tiny, dense center. The electrons must be somewhere outside the nucleus, leaving most of the atom as empty space.



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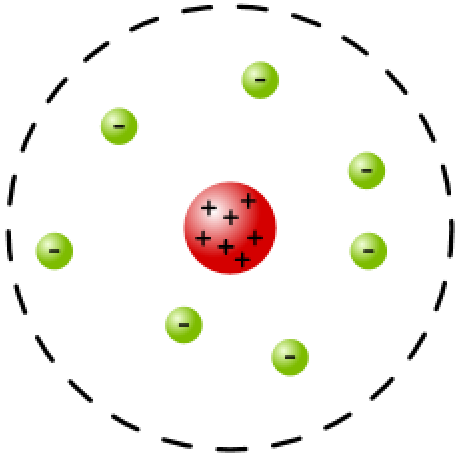
Rutherford’s Model of the Atom

- Rutherford proposed that the atom has a **small, dense nucleus** at its center. The nucleus contains **all the positive charge** and **almost all the mass** of the atom.
- The **electrons** are located outside the nucleus, moving around it like planet around the sun.
- Most of the atom is **empty space**, which is why most alpha particles passed straight through the gold foil in his experiment.
- This is still the starting point for how we think about atoms today.



Source: Wikipedia

Problem with Rutherford’s Atomic Model

- There are many problems with Rutherford Atomic Model many of which we will discuss in quantum mechanics lecture.
- If the nucleus is full of positive charge, those positive charge particle should try to fly apart because of **electrostatic repulsion.**
- Yet they stay packed tightly in a space about 10^{-15} meters wide — much smaller than the atom itself.
- The answer is there are other particles in nucleus called neutron which are bound to proton by strong nuclear force.
- I will explain this when we study forces.

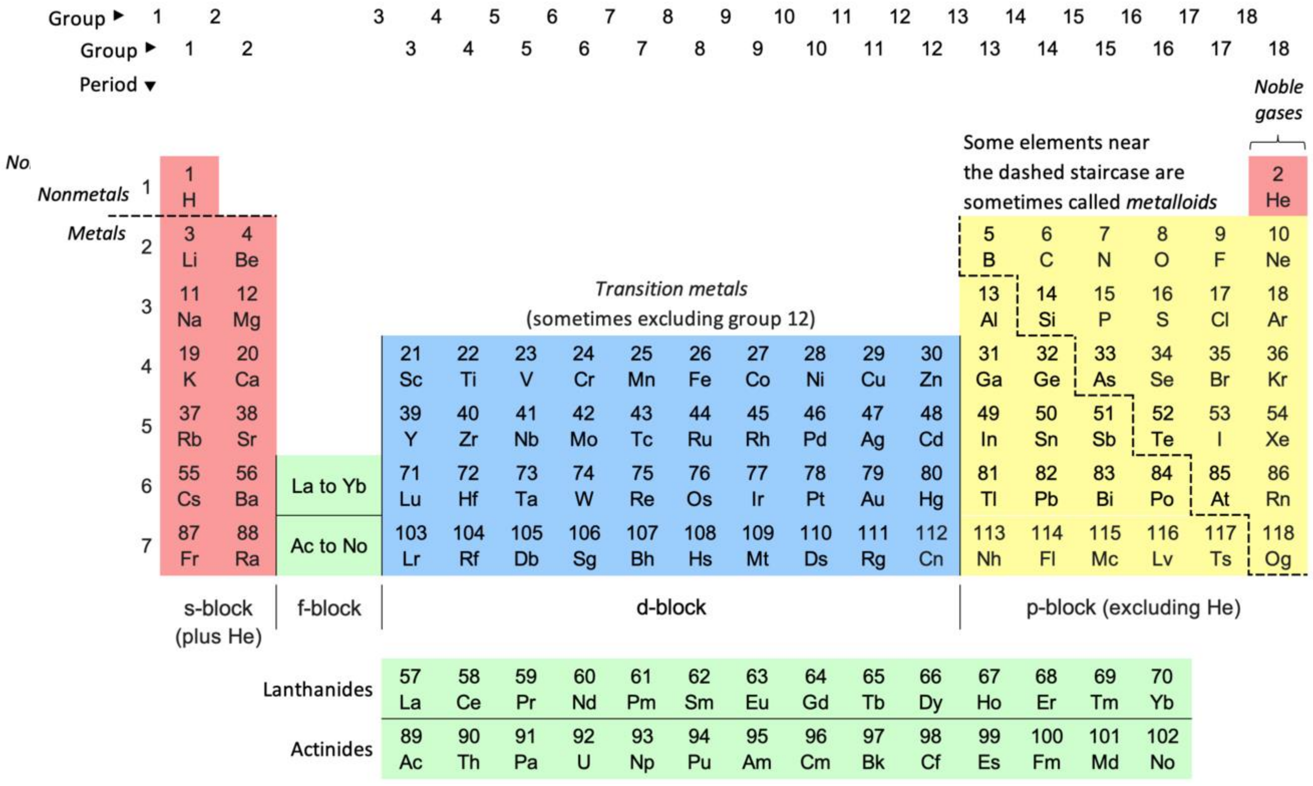
Question to Think About

Can the atomic nucleus be made up of protons and electrons? If not, why is this impossible and if yes, how would it work?

Atoms

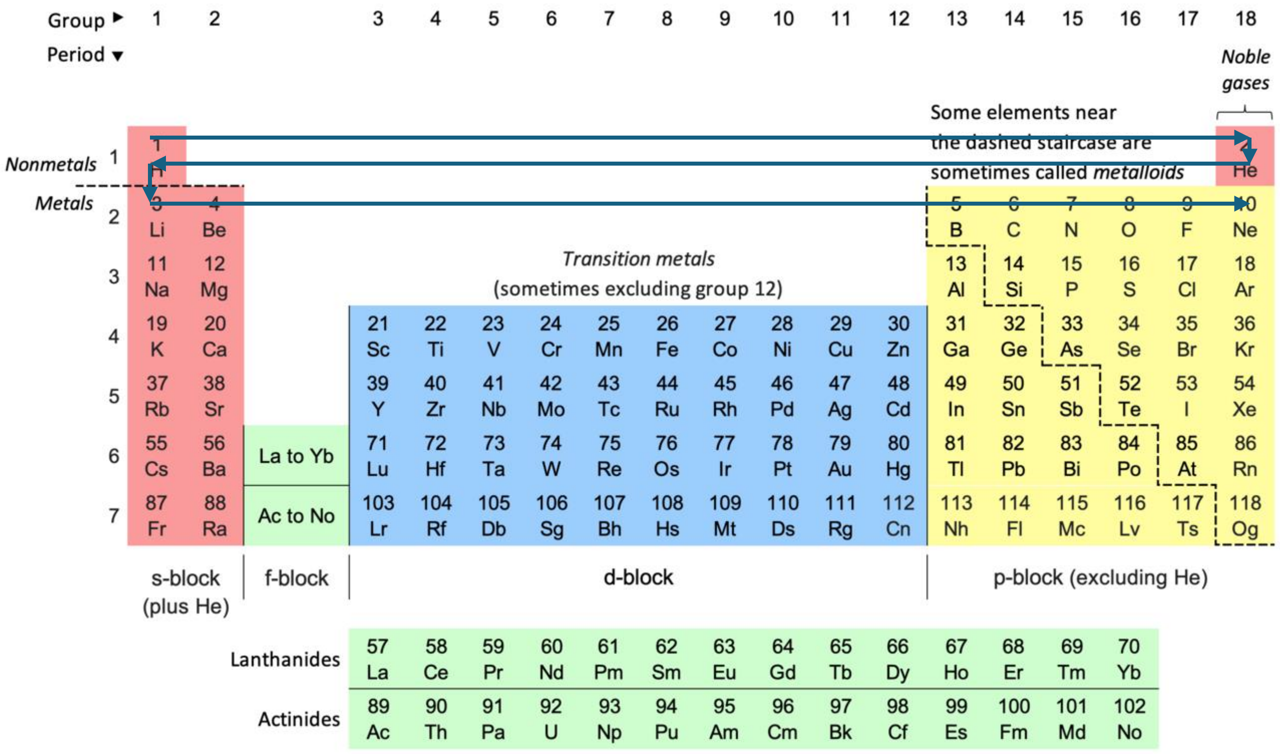
Atoms

In 1869, Dmitri Mendeleev organized the chemical elements into what became the famous Periodic Table.



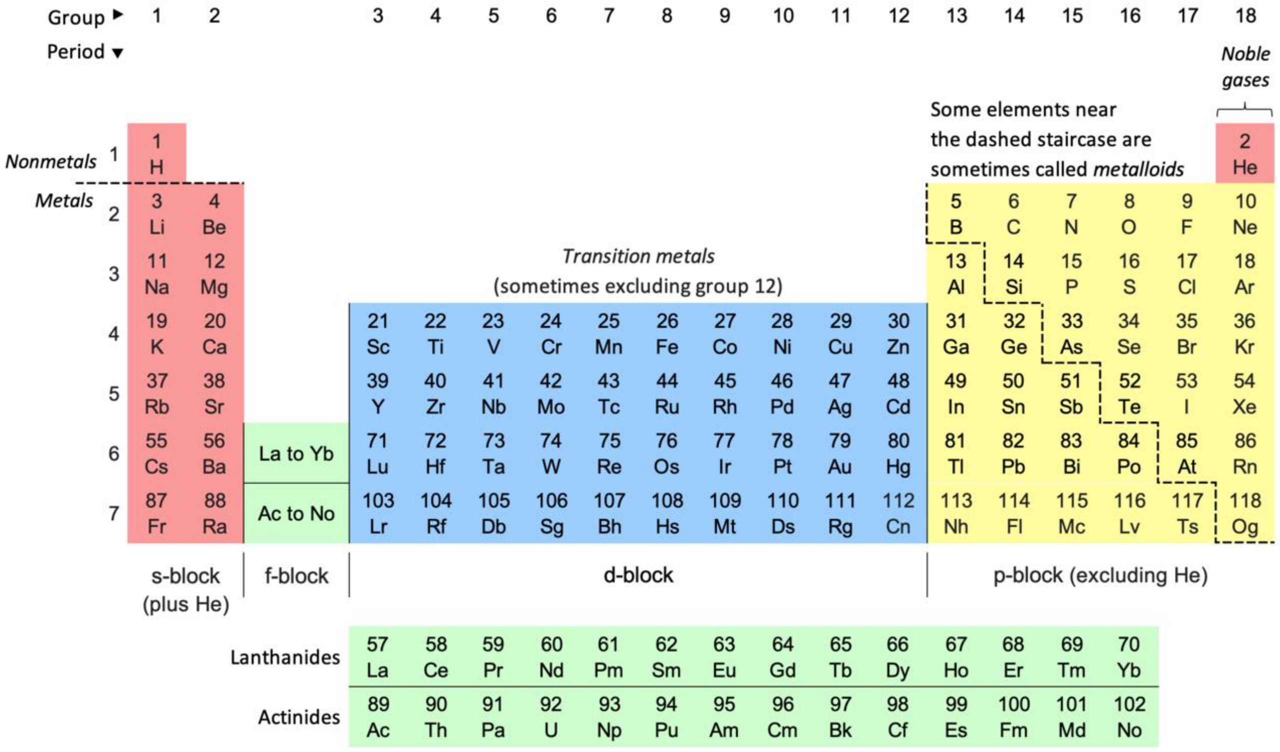
Atoms

With the lightest elements positioned at the top left and their masses increasing as you go row by row toward the bottom right



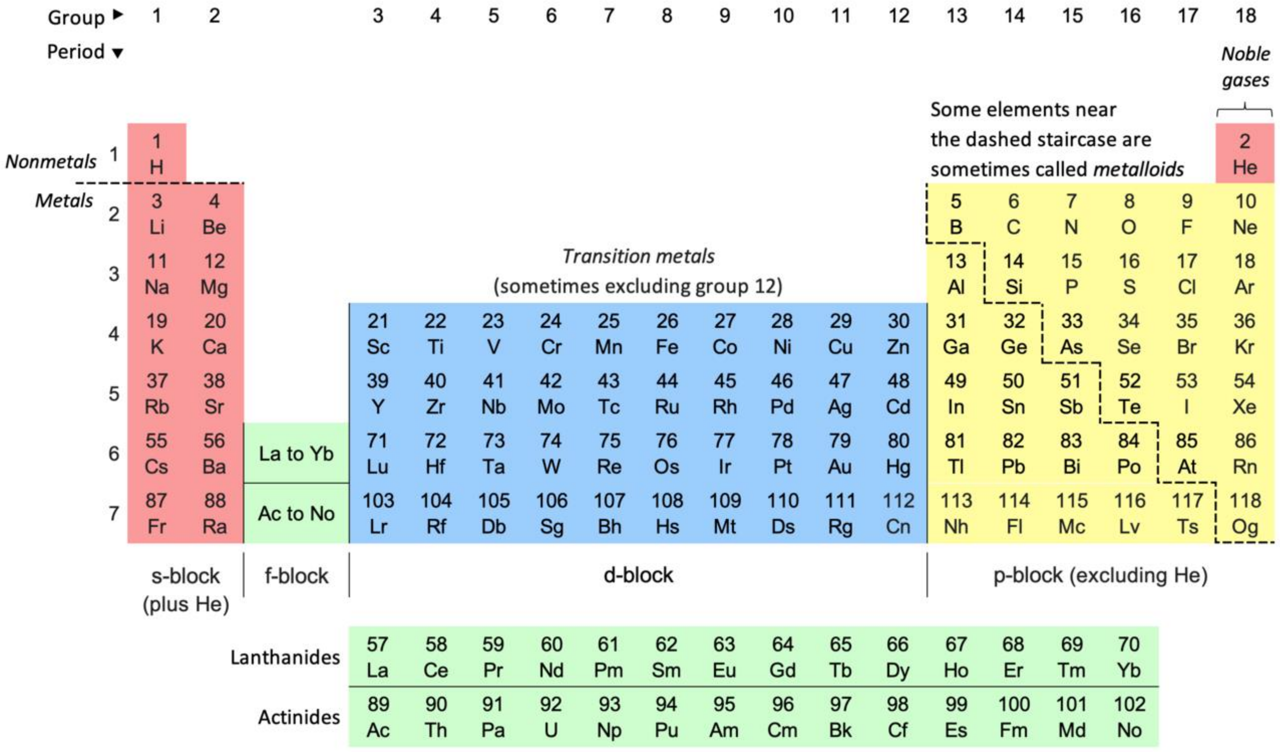
Atoms

The vertical columns group together elements with similar chemical properties, from the very reactive alkali metals on the far left to the chemically inert noble gases on the far right.



Atoms

At that time, Mendeleev's table had three noticeable gaps, which were later filled by the discovery of gallium, scandium, and germanium.



Atoms

Mendeleev did not know why the elements followed such a neat pattern — this was long before

- Thomson discovered the electron.
- Rutherford discovered the nucleus.
- Bohr proposed his theory of hydrogen.
- Not to mention Schrödinger's equation and quantum mechanics.

Once these discoveries were made, the periodic pattern was fully explained.

Things We Learned from the Periodic Table

- By looking at the pattern, we predicted new elements which was found later on.

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- Such a pattern told us that there was something going on at the fundamental level.
- We will repeat this same procedure when we will talk about quarks later in this lecture.

Radioactivity

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Source: Wikipedia

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- The number of protons decides what element it is (hydrogen, helium, uranium, etc.).
- The number of neutrons can vary — that’s what makes **isotopes**.

Source: Wikipedia

Radioactivity

Examples:

- Hydrogen normally has **0 neutrons**, but there are also versions with 1 neutron (deuterium) or 2 neutrons (tritium).

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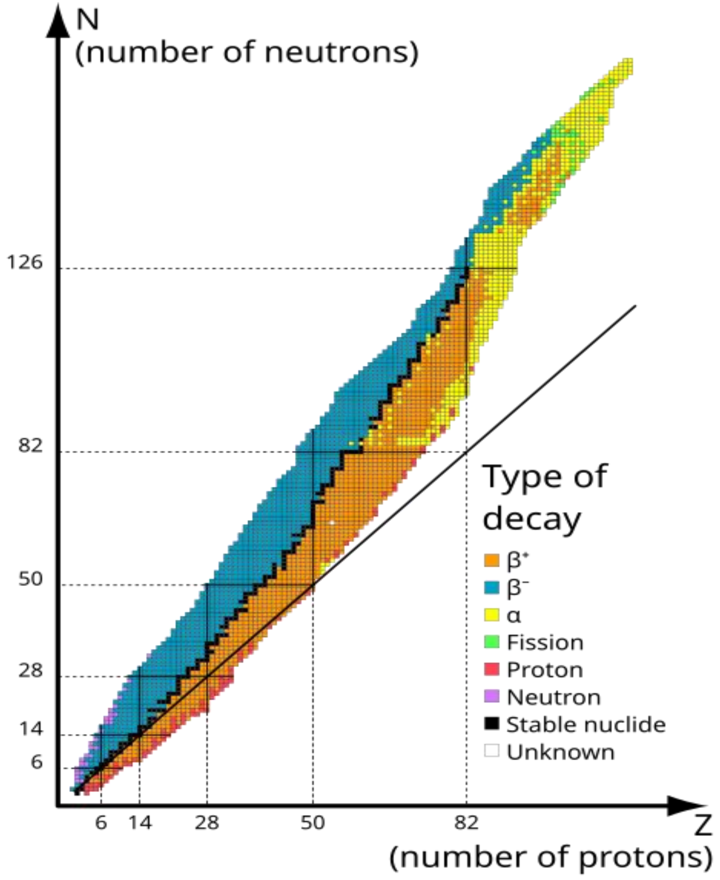
- Helium usually has **2 neutrons**, but a few isotopes have just 1.
- Isotopes of the same element behave the same in chemistry (since chemistry depends only on valence electrons), but their nuclei are different. [Biological and physical process can differ]

Radioactivity

- A nucleus is stable only if it has the right mix of protons and neutrons.



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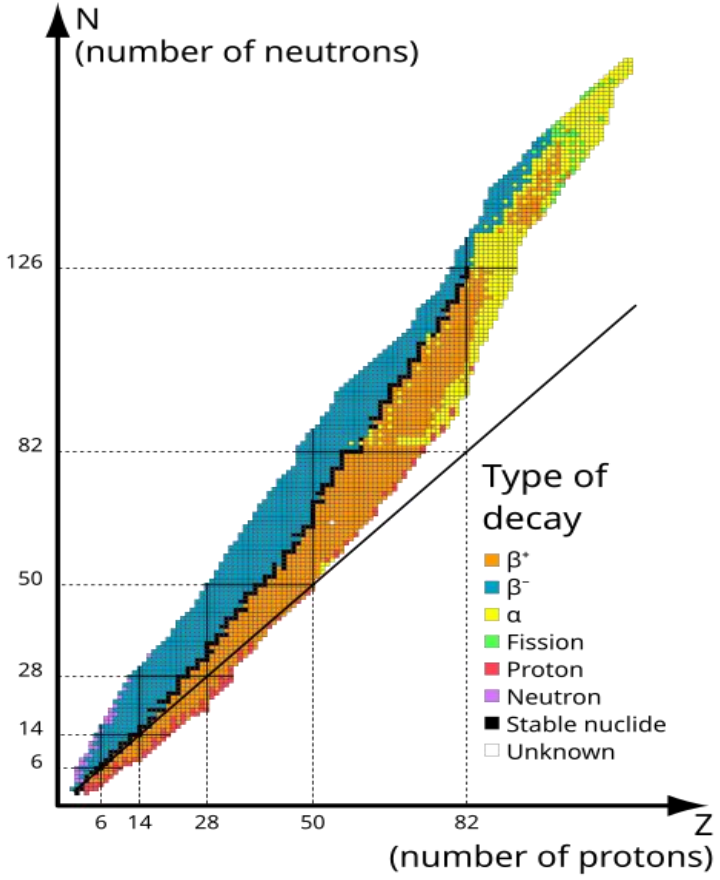

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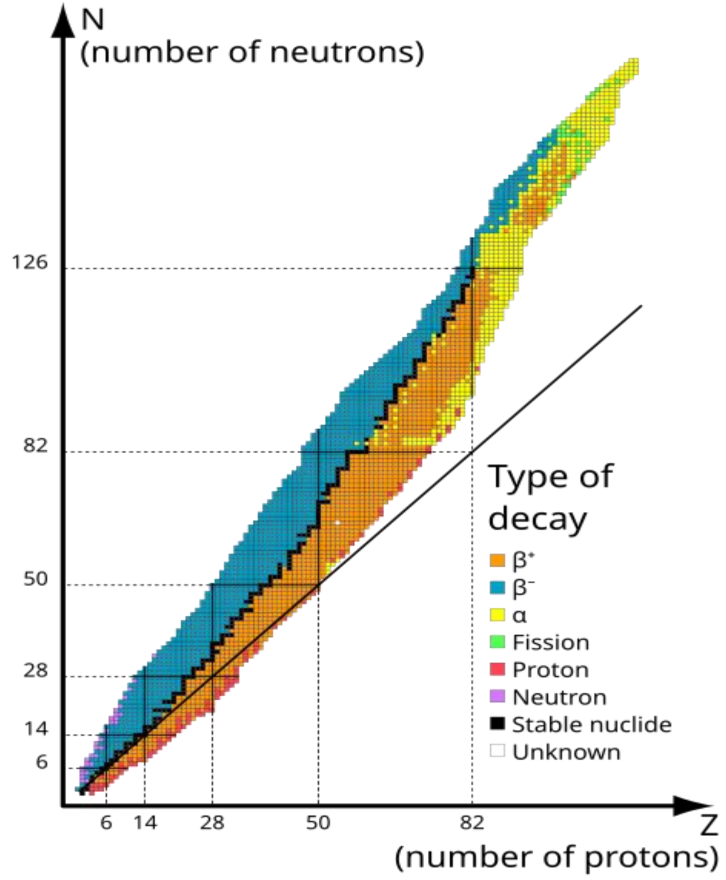

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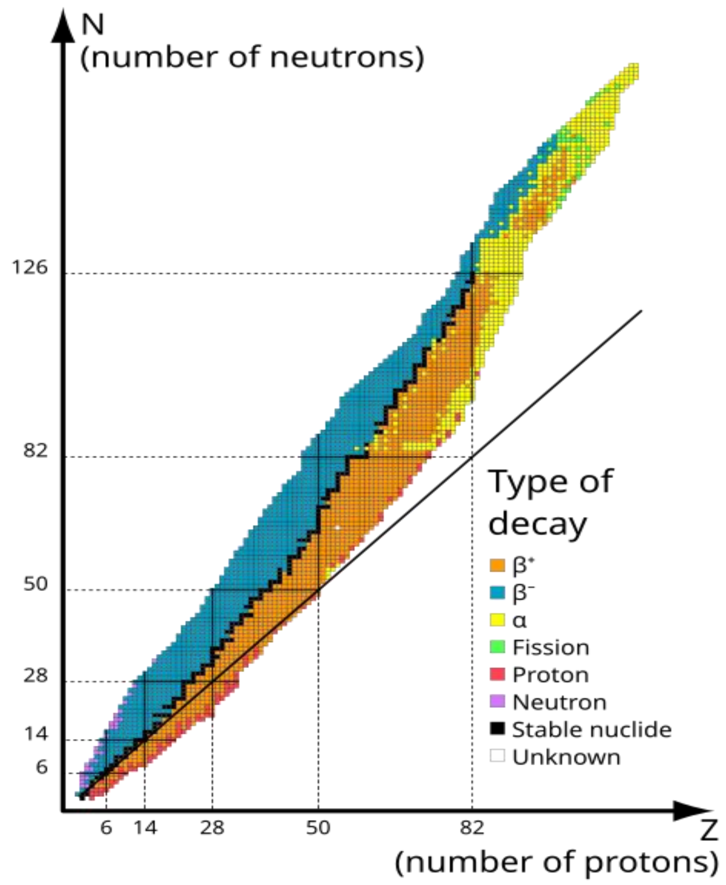

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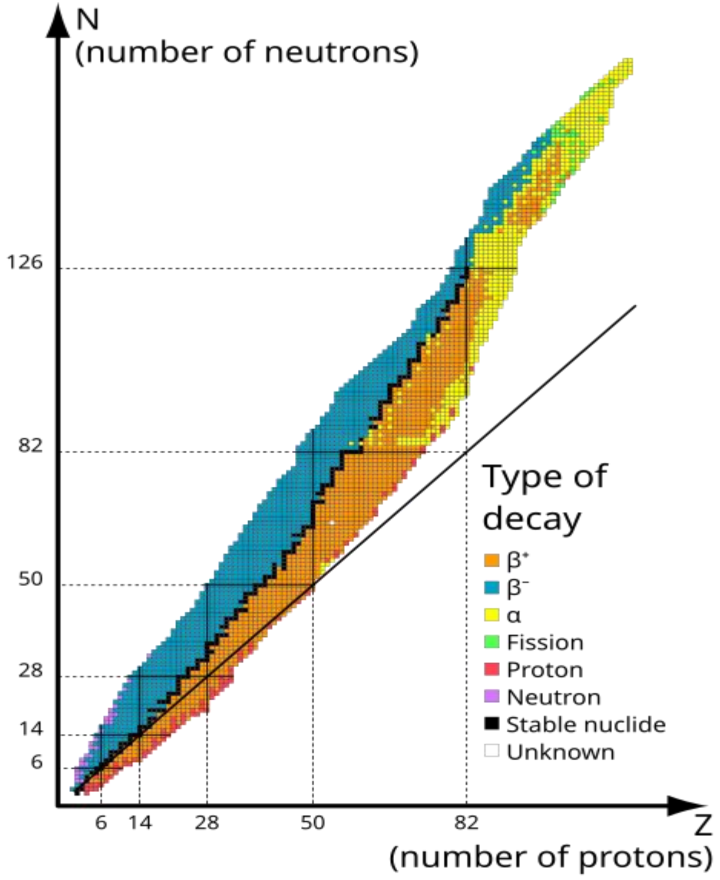
- If there are **too many neutrons** beyond what's needed, the nucleus also becomes unstable.



Source: Wikipedia

Radioactivity

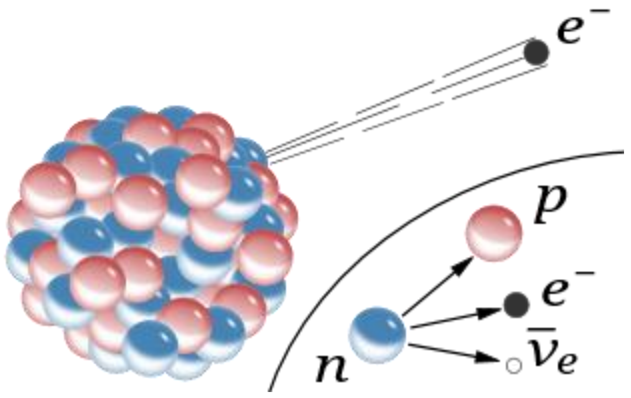
- If a nucleus has **too many neutrons**, you might think it would just "spit one out." This does happen sometimes — for example

$$^{13}Be \rightarrow \ ^{12}Be + n$$

Radioactivity

But usually, the extra neutrons solve the problem a different way: a neutron inside the nucleus changes into a **proton + an electron**.

- The proton stays in the nucleus.
- The electron gets ejected.
- This process is called **beta decay**. The electron that flies out is called a **beta particle**.



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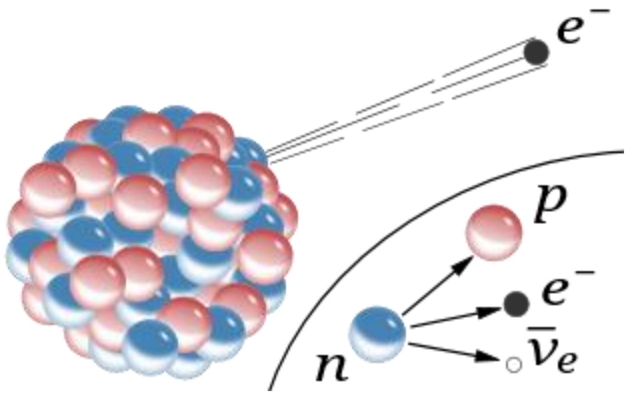
You also get neutrino in beta decay, but more on this later.



Radioactivity

If a nucleus has **too many protons** (or too few neutrons), what would you might you expect ?

A) It undergoes **beta-minus decay** (a neutron changes into a proton + electron).
B) It undergoes **beta-plus decay** (a proton changes into a neutron + positron).
C) It may eject a **proton** (proton emission, though rare).
D) In heavy nuclei, it may undergo **alpha decay** (release of 2 protons + 2 neutrons).

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Instead, there are more common ways:

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  - Example: $^{22}Na \rightarrow {}^{22}Ne + \beta^{+}(e^{+})$

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  - Example: $^{22}Na \rightarrow {}^{22}Ne + \beta^{+}(e^{+})$
- **Alpha decay (in heavy nuclei):** The nucleus releases an **alpha particle** (2 protons + 2 neutrons, same as a helium-4 nucleus).
  - Example: $^{238}U \rightarrow {}^{234}Th + \alpha$

The Middle Period (1930-1956)

Photon

Photon

- I am going to skip over this but we will study photon in detail in quantum mechanics lecture.

Anti-Particles

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It predicted two kinds of energy solutions:

- A positive energy solution: $E = +\sqrt{p^2c^2 + m^2c^4}$
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Because systems naturally move toward **lower energy**, the negative-energy solutions seemed to mean that an electron could keep “falling” into lower and lower (more negative) energy states. If that were true, the electron would **run away endlessly**, releasing infinite energy — which is clearly unphysical.

Anti-Particles

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Anti-Particles

- One solution would be to throw away the negative energy solution by calling them unphysical as we do it often in mathematics and physics.
- But you can’t do that in quantum mechanics, you need to work in complete set of states, and positive energy solutions alone are not complete. [Beyond the scope of this course but good to keep in mind]

Anti-Particle

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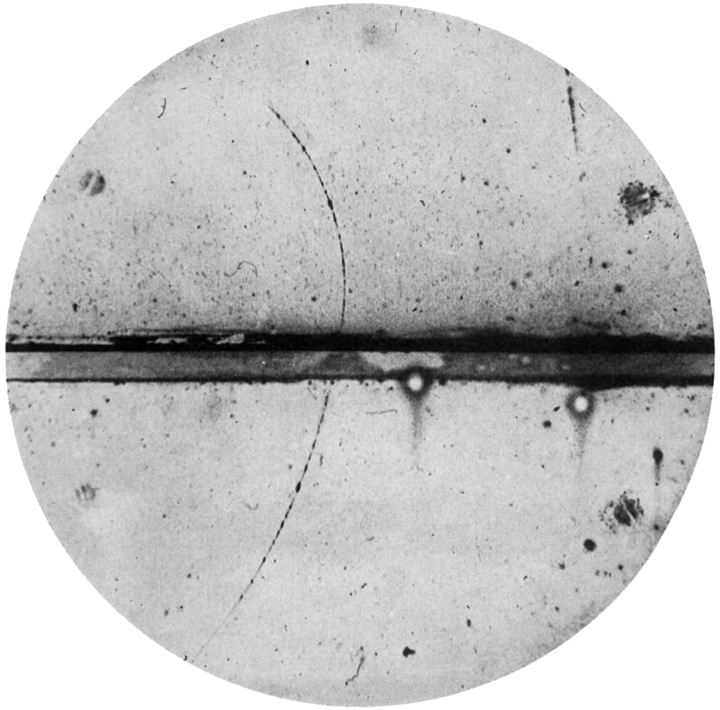
- Feynman–Stückelberg picture, the negative-energy solutions are reinterpreted as **positive-energy states of a different particle.**
- Dirac's theory implied that for every particle there should be an **antiparticle** with the same mass but opposite electric charge.

Anti-Particle

- The **positron** (the electron's antiparticle) was discovered in 1932 by Carl Anderson in cosmic ray tracks.



The first photograph of track made by positron by Carl Anderson (Source: Wikipedia).

Anti-Particle

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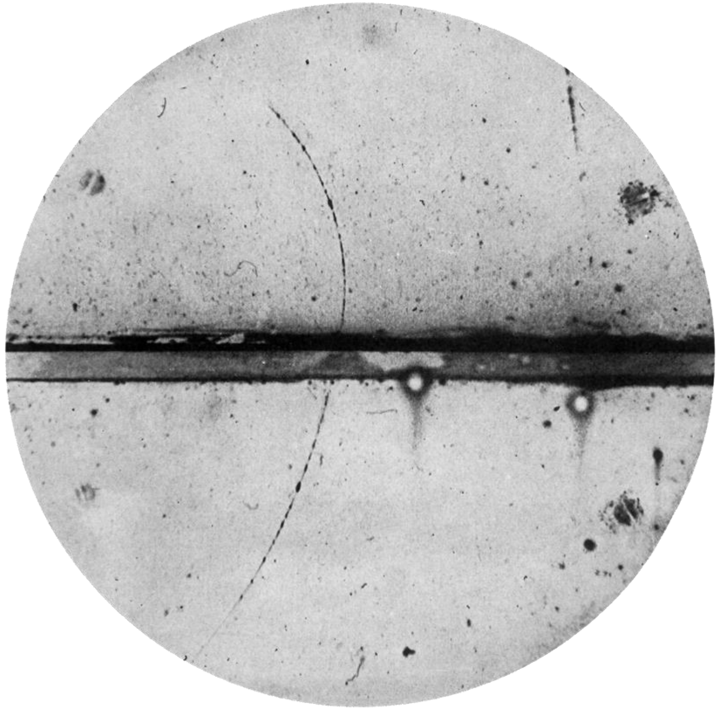
- Later, the **antiproton** (1955) and the **antineutron** (1956) were also discovered at Berkeley Bevatron.



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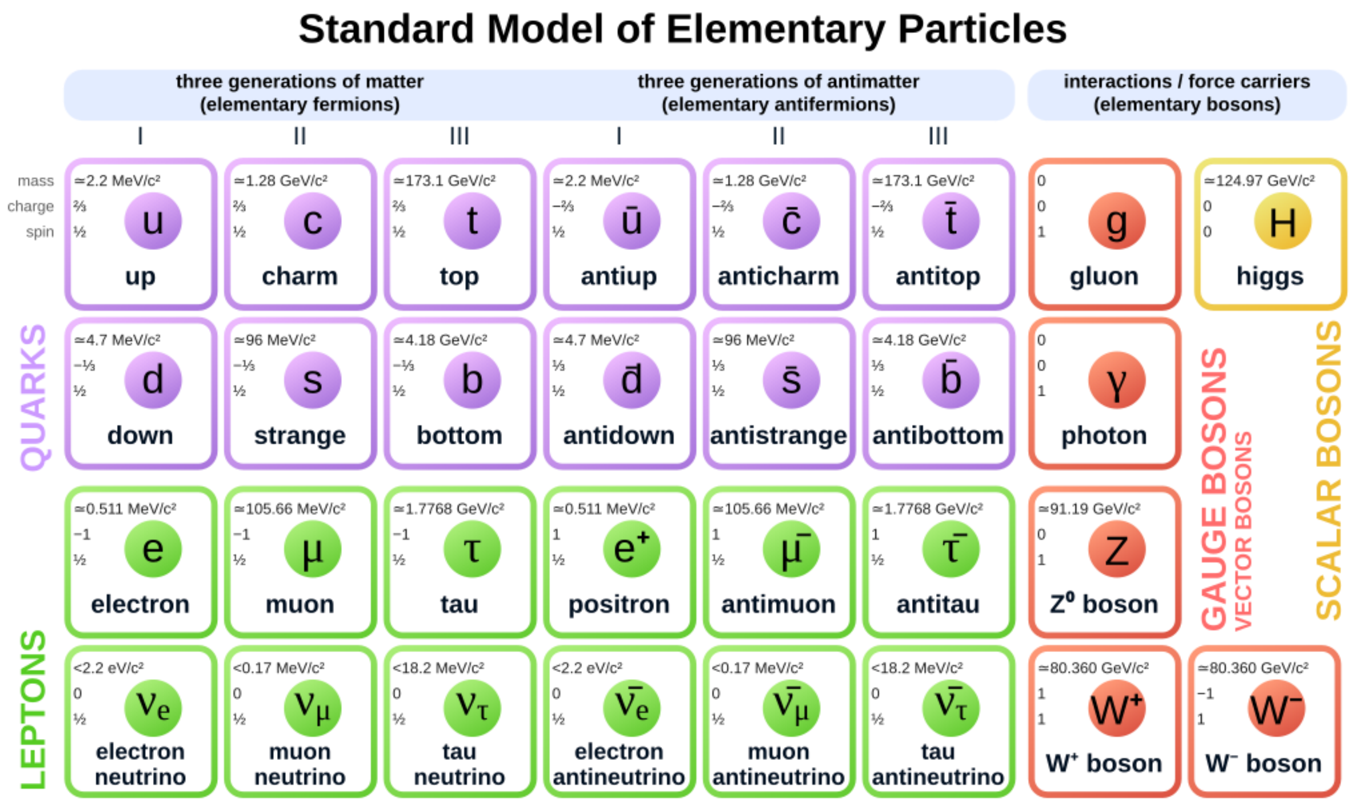
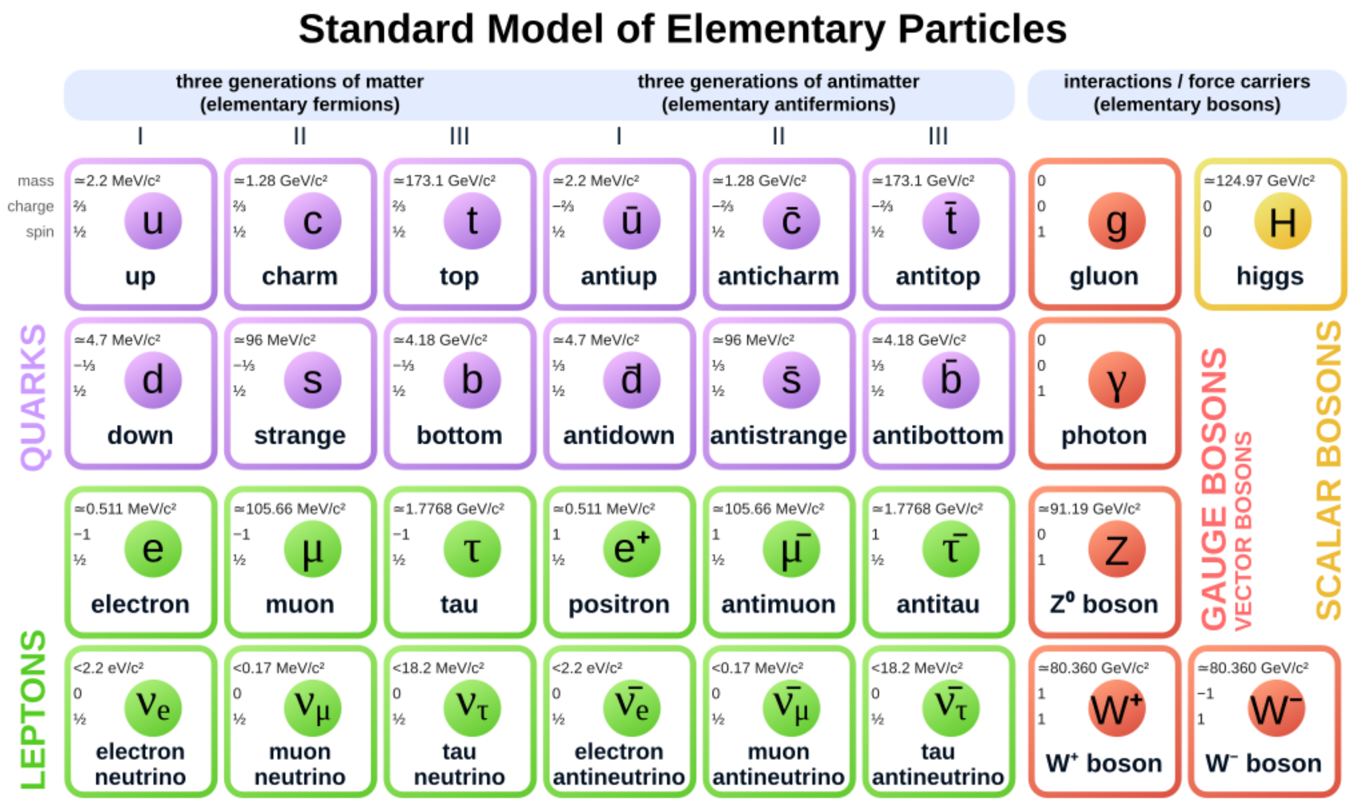


Source: Wikipedia

Anti-Particles

- Every elementary particle has a corresponding antiparticle.

- An exception occurs with certain electrically neutral particles which are their own antiparticles. For example the photon.



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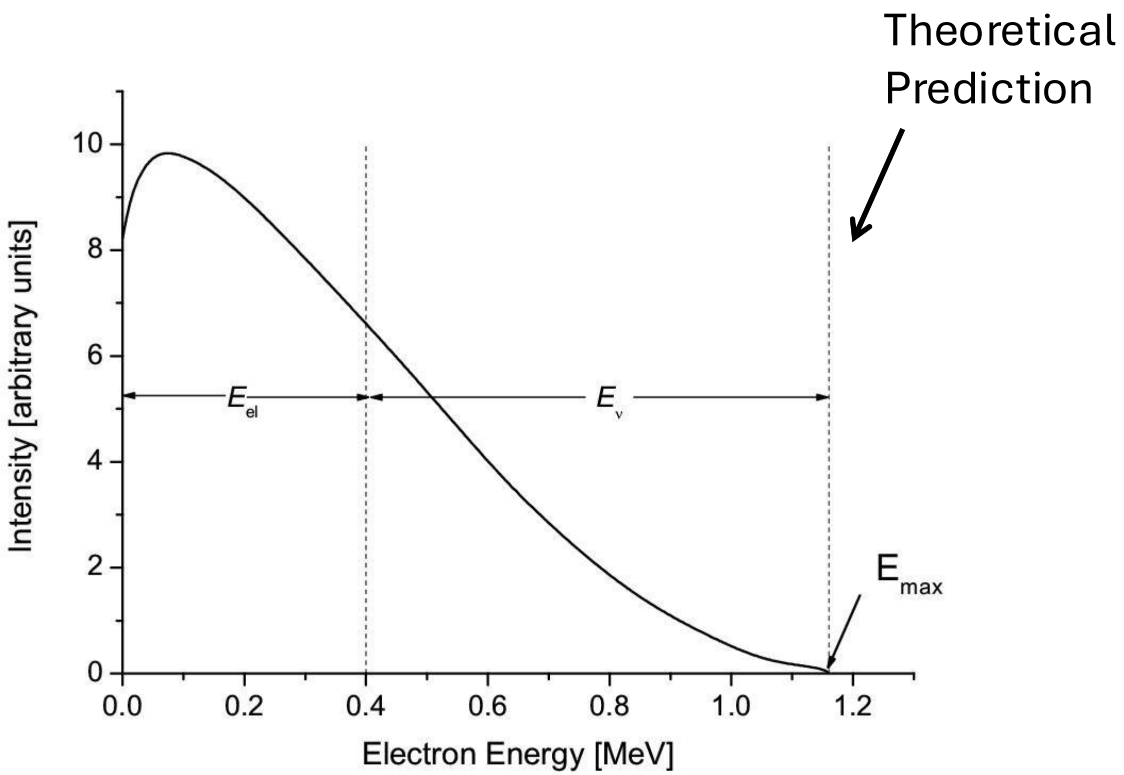

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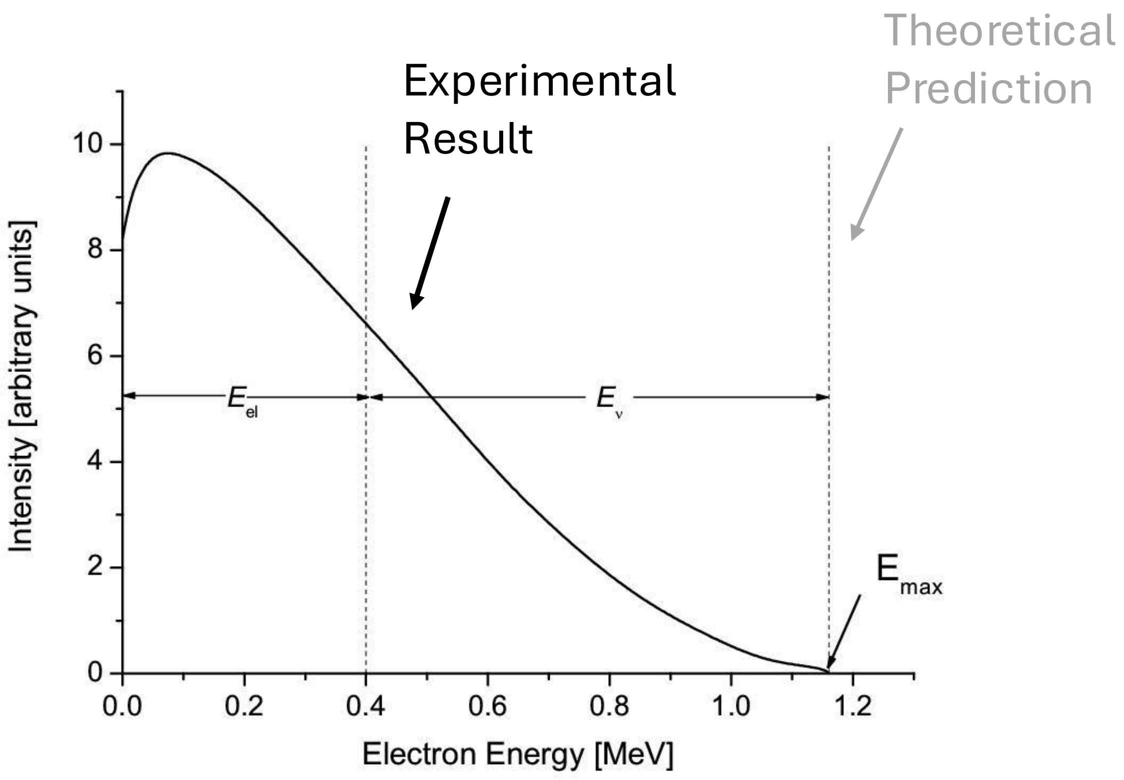
- But experiments showed the electrons had a **range of energies**.



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- But Wolfgang Pauli suggested a better idea: a new, invisible particle must be carrying away the missing energy. He called it the **“neutron.”**
- In 1932, James Chadwick discovered the actual neutron (the heavy neutral particle in nuclei), so Enrico Fermi renamed Pauli’s lighter invisible particle the **neutrino** (meaning “little neutral one”).

Neutrinos

- Enrico Fermi took Pauli’s idea seriously and, in 1933, built a highly successful mathematical theory of beta decay that included Pauli’s new particle, which he named the **neutrino** (ν, the Greek letter “nu”):

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$$n \rightarrow p + e^- + \nu_e$$

- The energy is now shared by the electron and the neutrino, and that explains why some electrons have more, and some less, up to a maximum of E.

Neutrinos

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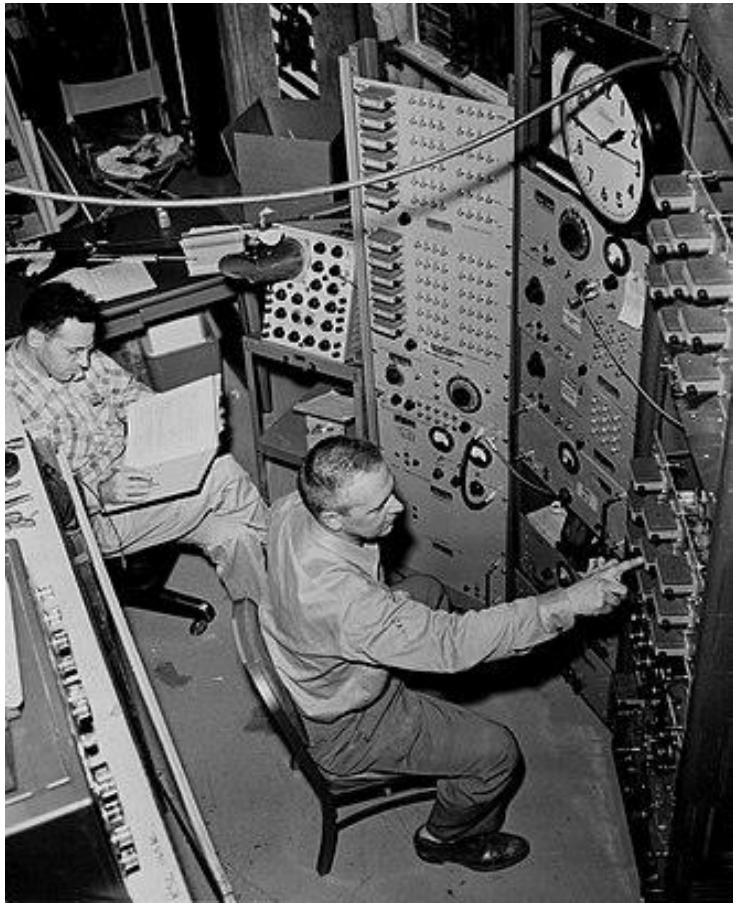
- Every second, **hundreds of billions of neutrinos from the Sun** pass straight through your thumb.

Neutrinos

- Because they interact so weakly, neutrinos weren't detected until **1956**, when Frederick Reines and Clyde Cowan set up detectors near the **Savannah River nuclear reactor**, which produces huge numbers of neutrinos.



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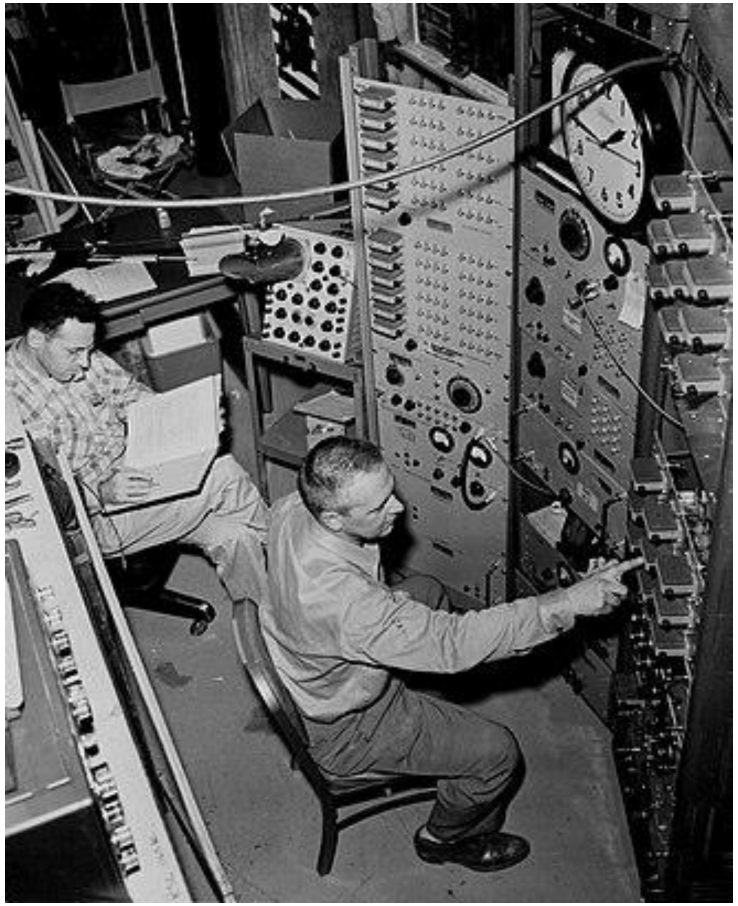

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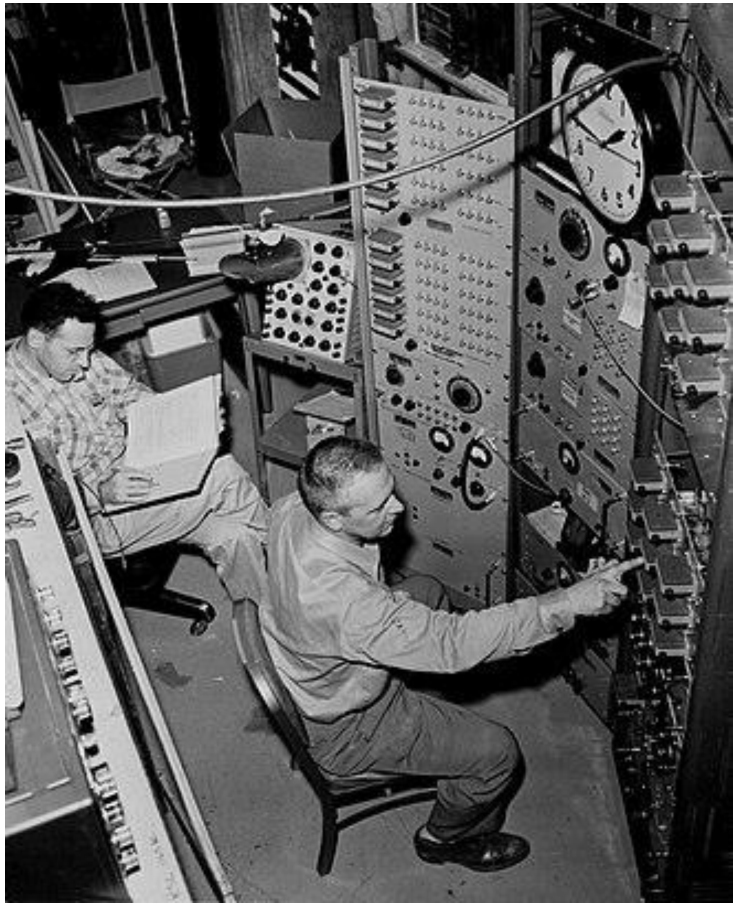
- This experiment provided the first direct detection of neutrinos and proved that they were real particles, not just a theoretical idea.



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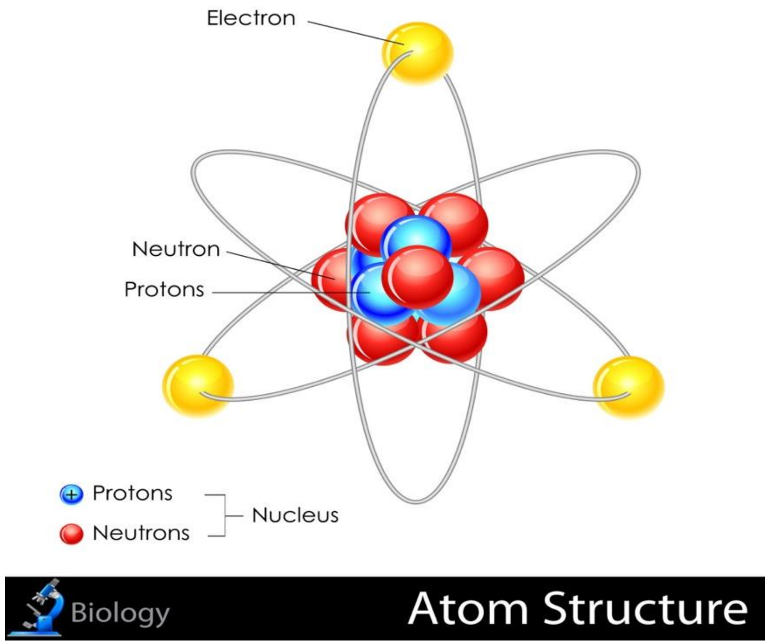
- But in 2001, experiments on **neutrino oscillations** showed that neutrinos actually do have a **small but nonzero mass**. To this day, the exact value of that mass is still unknown.
- It was wrong to assume neutrino mass to be zero at the first place. More on this in neutrino theory lecture.

Meson

Meson

- Atoms were first explained using three particles — **electrons, protons, and neutrons.**



Source: https://kidspressmagazine.com/science-for-kids/misc/structure-atoms.html

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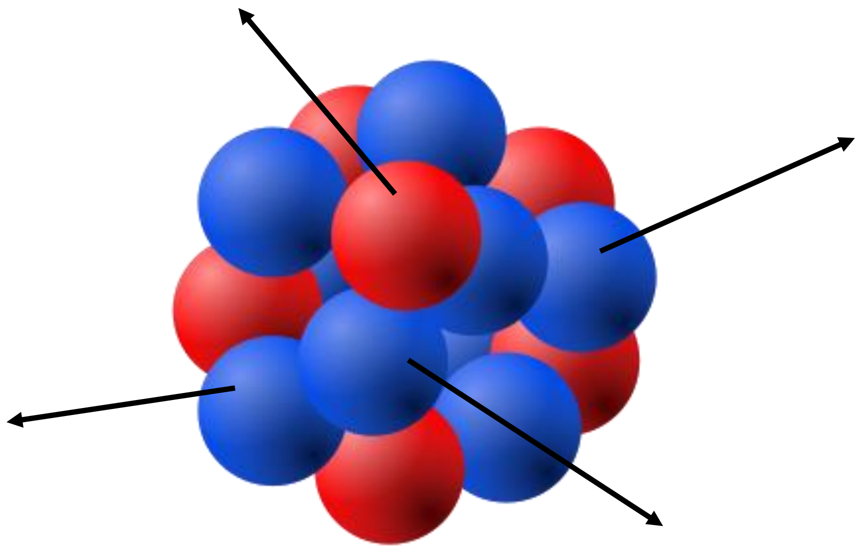
Meson

But this raised a big question:

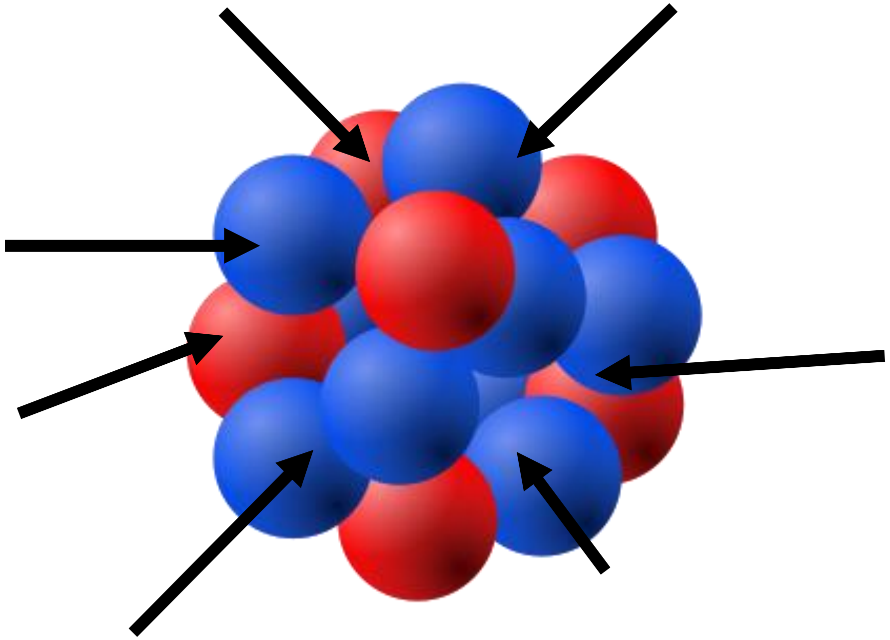
- If protons are all positively charged and repel each other, why doesn’t the nucleus fly apart?
- And since neutrons have no charge, why don’t they just drift away?



Source: Wikipedia

Meson

- The answer is that there must be another, much stronger force that holds protons and neutrons together inside the nucleus. Physicists called it the **strong force**.



Meson

- Actually, what holds the nucleus together is not the full fundamental strong force itself, but the **residual strong force**, which we call the **strong nuclear force**. I will explain this in some detail when we study particle interactions.

Meson

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If boson is massless, the force is long range (for example electromagnetic force.)

Meson

Let’s go back to this residual strong force.

Question. If the strong nuclear force is so powerful, why don’t we notice it in everyday life?
A) Because it only acts on electrons
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- But in 1937, experiments with **cosmic rays** seemed to find just such particles, matching his idea of a “middle-weight” meson.

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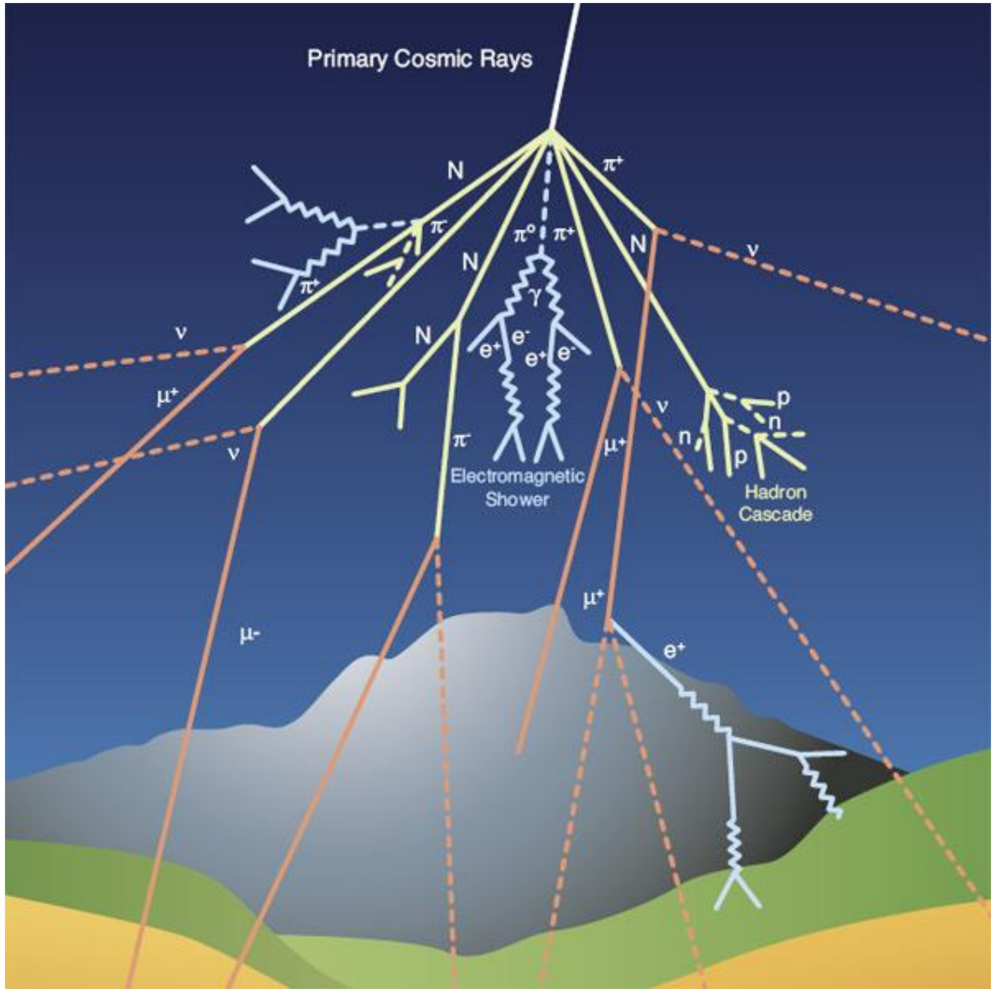
- In 1946, experiments in Rome showed that these cosmic ray particles interacted only **weakly** with nuclei.
- If they were really Yukawa's mesons, responsible for the **strong force**, the interaction should have been very large.

Meson

In 1947, Cecil Powell and his team solved the mystery of the cosmic ray particles. They discovered that there are actually **two different middle-weight particles.**



Source: CERN

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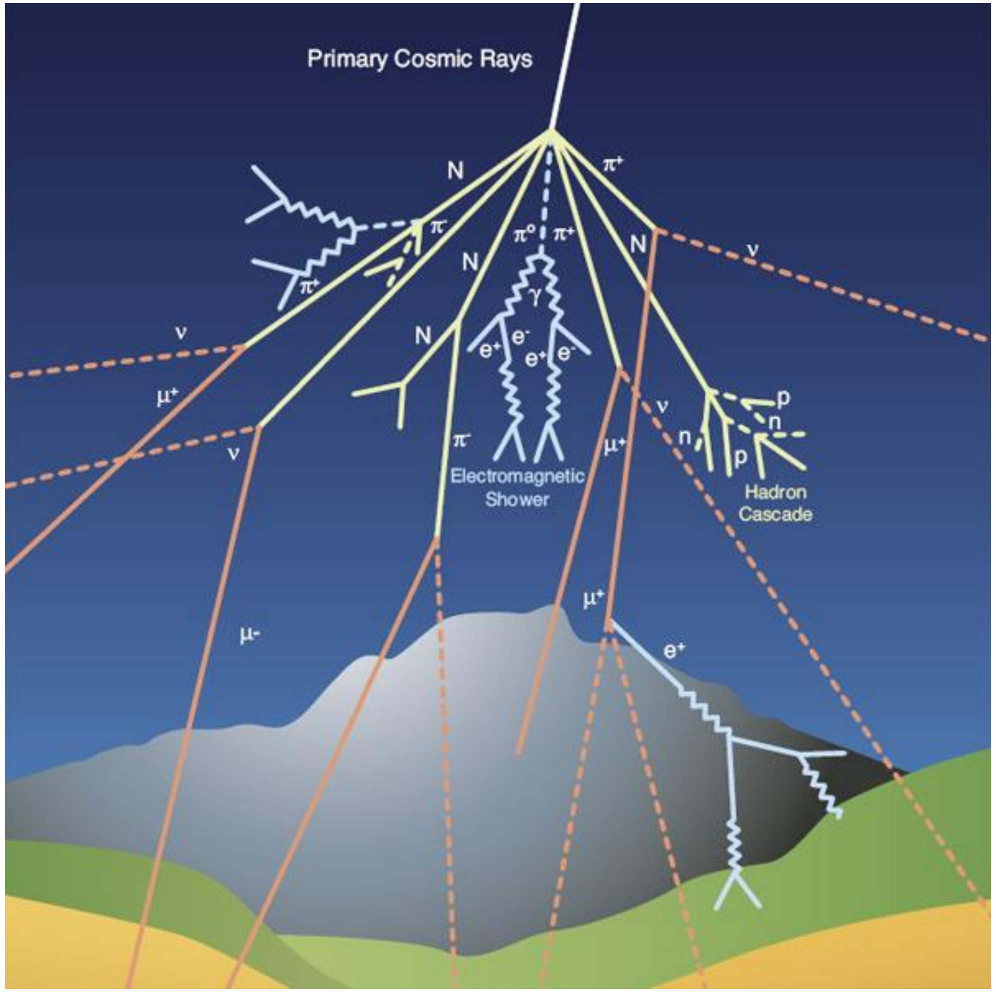

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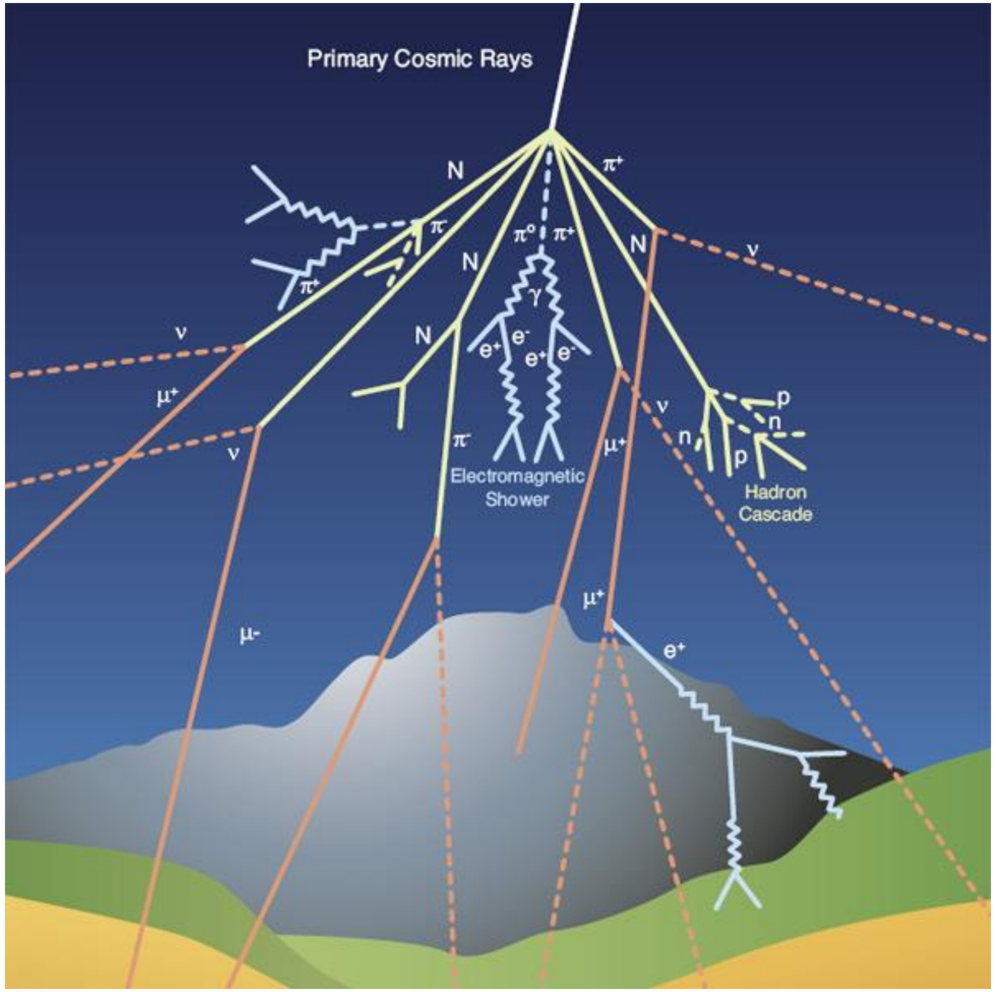

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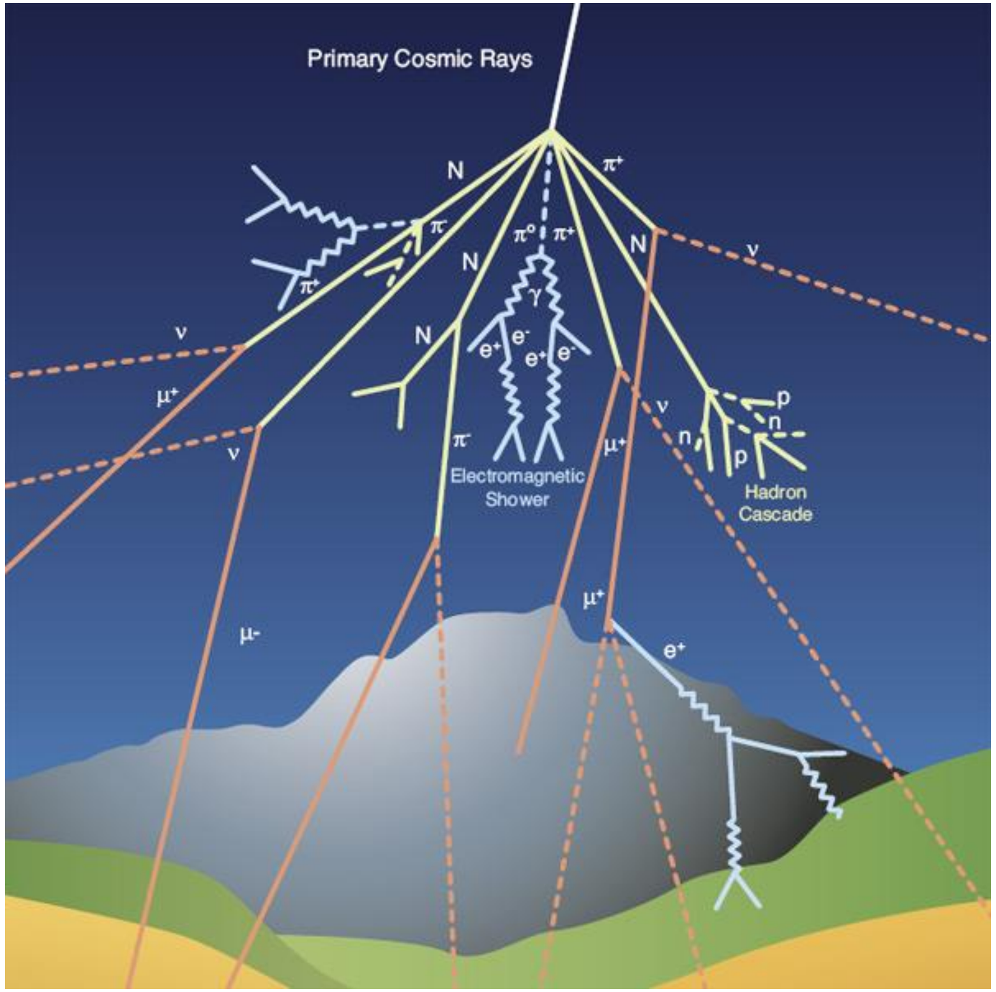
It turned out that the **muon was an impostor**. It doesn't take part in the strong force at all; instead, it behaves just like a **heavy version of the electron**, so it belongs to the **lepton family**.



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Strange Particles

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- Still, many physicists thought the big problems of elementary particle physics were solved.

Strange Particles

- The sense of “completion” in 1947 didn’t last. Later that year, cosmic ray studies revealed **new, unexpected particles**, so surprising that they were called **strange particles**.

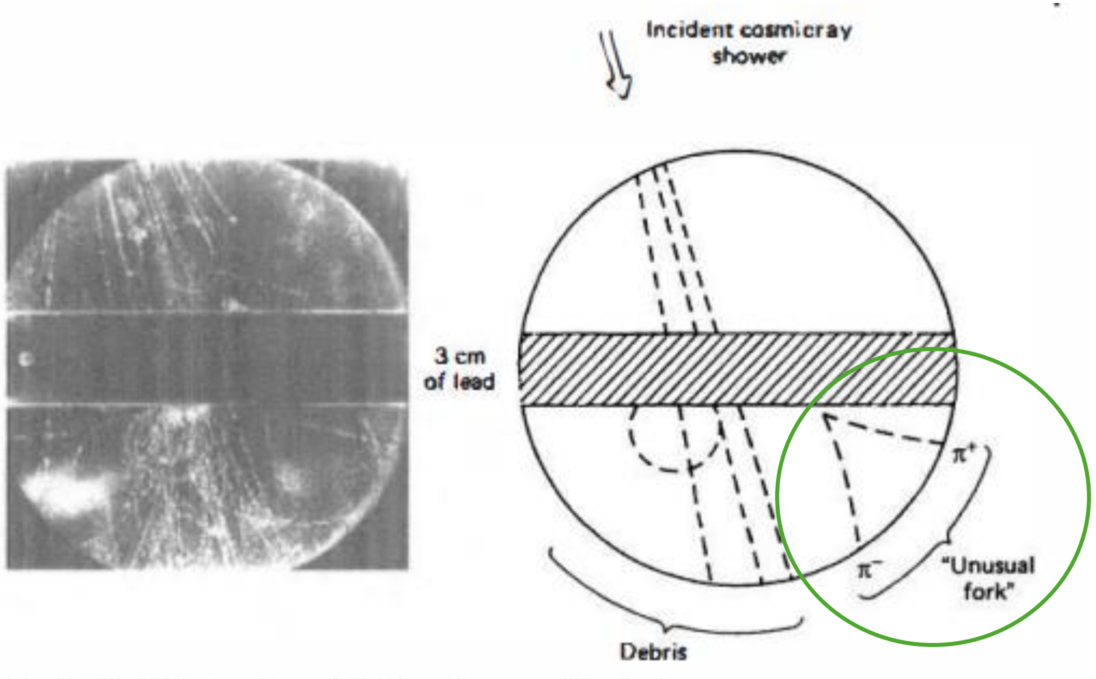

Fig. 1.7 The first strange particle. Cosmic rays strike a lead plate, producing a K^0, which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. Rochester, G. D. (© 1947). Nature, 160, 855. Copyright Macmillan Journals Limited.)

Strange Particles

- The sense of "completion" in 1947 didn't last. Later that year, cosmic ray studies revealed **new, unexpected particles**, so surprising that they were called **strange particles**.
- **Rochester and Butler** took a famous cloud chamber photo: cosmic rays hit a lead plate, creating a **new neutral particle** that decayed into two oppositely charged tracks (forming a "Y" shape). This was evidence for a particle heavier than the pion, later called the **kaon (K)**.

$$K^0 \rightarrow \pi^- + \pi^+$$

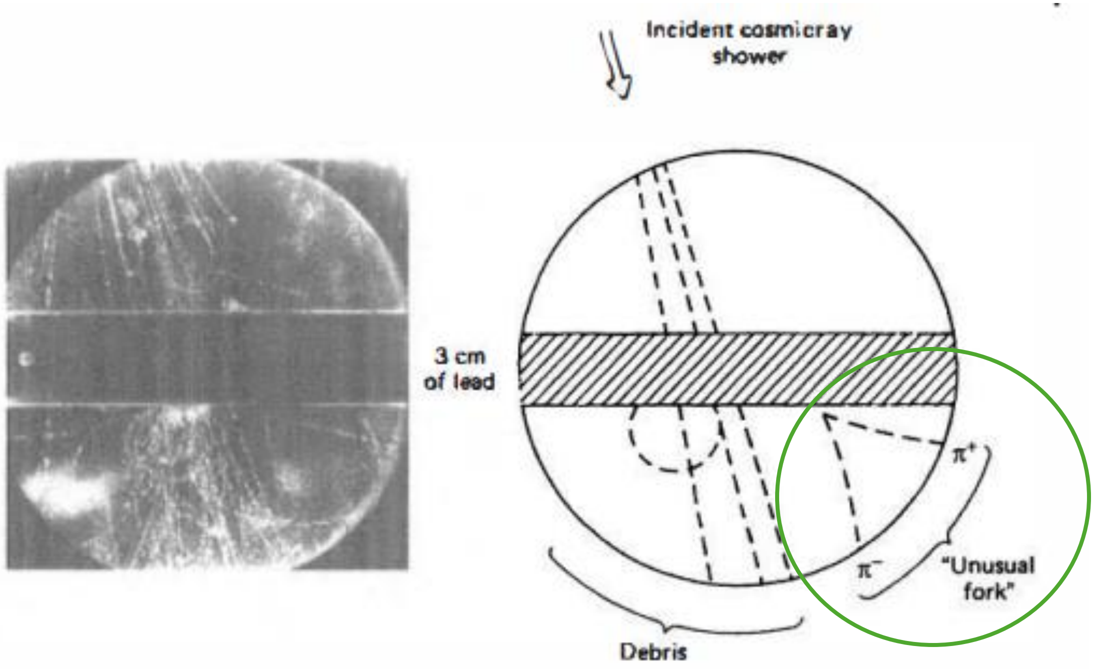

Fig. 1.7 The first strange particle. Cosmic rays strike a lead plate, producing a K^0, which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. Rochester, G. D. (© 1947). Nature, 160, 855. Copyright Macmillan Journals Limited.)

Strange Particles

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Strange Particles

- Some acted like heavier versions of the **proton and neutron**, so they were put into the **baryon family**.
- Others acted like heavier versions of the **pion**, so they were placed in the **meson family.**

Strange Particles

Baryons

Appearance hide

$J^P = \frac{1}{2}^+$ baryons

Particle name	Symbol	Quark content	Rest mass (MeV/c^2)	I	J^P	Q (e)	S	C	B'	Mean lifetime (s)	Commonly decays to
proton[8]	p, p^+, N^+	uud	938.272 0813(58) [a]	$\frac{1}{2}$	$\frac{1}{2}^+$	+1	0	0	0	stable[b]	unobserved
neutron[9]	n, n^0, N^0	udd	939.565 4133(58) [a]	$\frac{1}{2}$	$\frac{1}{2}^+$	0	0	0	0	$(8.794 \pm 0.006) \times 10^{+2}$[c]	$p^+ + e^- + \bar{\nu}_e$
lambda[10]	Λ^0	uds	1 115.683 ± 0.006	0	$\frac{1}{2}^+$	0	−1	0	0	$(2.632 \pm 0.020) \times 10^{-10}$	$p^+ + \pi^-$ or $n^0 + \pi^0$
charmed lambda[11]	Λ_c^+	udc	2 286.46 ± 0.14	0	$\frac{1}{2}^+$	+1	0	+1	0	$(2.024 \pm 0.031) \times 10^{-13}$	see Λ_c^+ decay modes
bottom lambda[12]	Λ_b^0	udb	5 619.6 ± 0.17	(0)	$(\frac{1}{2}^+)$	0	0	0	−1	$(1.471 \pm 0.009) \times 10^{-12}$	see Λ_b^0 decay modes
sigma[13]	Σ^+	uus	1 189.37 ± 0.07	1	$\frac{1}{2}^+$	+1	−1	0	0	$(8.018 \pm 0.026) \times 10^{-11}$	$p^+ + \pi^0$ or $n^0 + \pi^+$
sigma[14]	Σ^0	uds	1 192.642 ± 0.024	1	$\frac{1}{2}^+$	0	−1	0	0	$(7.4 \pm 0.7) \times 10^{-20}$	$\Lambda^0 + \gamma$
sigma[15]	Σ^-	dds	1 197.449 ± 0.030	1	$\frac{1}{2}^+$	−1	−1	0	0	$(1.479 \pm 0.011) \times 10^{-10}$	$n^0 + \pi^-$
charmed sigma[16]	$\Sigma_c^{++}(2455)$	uuc	2 453.97 ± 0.14	1	$\frac{1}{2}^+$	+2	0	+1	0	$3.48^{+0.37}_{-0.16} \times 10^{-22}$[d]	$\Lambda_c^+ + \pi^+$
charmed sigma[16]	$\Sigma_c^+(2455)$	udc	2 452.9 ± 0.4	1	$\frac{1}{2}^+$	+1	0	+1	0	$>1.43 \times 10^{-22}$[d]	$\Lambda_c^+ + \pi^0$

Meson

Appearance hide

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass [MeV/c^2]	I^G	J^{PC}	S	C	B'	Mean lifetime [s]	Co
Pion[10]	π^+	π^-	$u\bar{d}$	139.570 18 ± 0.000 35	1^-	0^-	0	0	0	$(2.6033 \pm 0.0005) \times 10^{-8}$	
Pion[11]	π^0	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$ [a]	134.9766 ± 0.0006	1^-	0^{-+}	0	0	0	$(8.52 \pm 0.18) \times 10^{-17}$	
Eta meson[12]	η	Self	$\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$ [a]	547.862 ± 0.018	0^+	0^{-+}	0	0	0	$(5.02 \pm 0.19) \times 10^{-19}$[b]	
Eta prime meson[13]	$\eta'(958)$	Self	$\frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$ [a]	957.78 ± 0.06	0^+	0^{-+}	0	0	0	$(3.32 \pm 0.15) \times 10^{-21}$[b]	$(\rho^0$
Charmed eta meson[14]	$\eta_c(1S)$	Self	$c\bar{c}$	2 983.6 ± 0.7	0^+	0^{-+}	0	0	0	$(2.04 \pm 0.05) \times 10^{-23}$[b]	See
Bottom eta meson[15]	$\eta_b(1S)$	Self	$b\bar{b}$	9 398.0 ± 3.2	0^+	0^{-+}	0	0	0	$(6.58 \pm 0.15) \times 10^{-23}$[b]	See
Kaon[16]	K^+	K^-	$u\bar{s}$	493.677 ± 0.016	$\frac{1}{2}$	0^-	1	0	0	$(1.2380 \pm 0.0021) \times 10^{-8}$	

Strange Particles

- In 1952, with the opening of the **Cosmotron accelerator** at Brookhaven, physicists could create strange particles in the lab (not just from cosmic rays), and the number of discoveries exploded.

Strange Particles

- When physicists studied collisions that produced **strange particles**, they noticed something unusual:

Strange Particles

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$$\pi^- + p \rightarrow K^+ + \Sigma^-$$

$$\pi^- + p \rightarrow K^0 + \Sigma^0$$

$$\pi^- + p \rightarrow K^0 + \Lambda$$

In each case, you get **two strange particles** in the final state.

Strange Particles

- What you **never** see is a reaction that produces **only one strange particle**, such as:

$$\pi^- + p \nrightarrow \pi^+ + \Sigma^-$$

Strange Particles

- This led Murray Gell-Mann to introduce the idea of a new conserved quantity called **strangeness** same as electric charge.
- Whenever strange particles are produced, their **total strangeness adds to zero**, so they must come in pairs.

Strange Particles

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- Kaons (K^+, K^-) were given **+1**.
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- He then proposed the **conservation of strangeness**: in reactions, the total strangeness before and after must be the same.

Strange Particles

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Strange Particles

- By 1960, particle physics had become a mess. In 1947, things seemed simple, but now scientists had discovered so many new particles that it looked like chaos.
- They could group them into three families:

  Leptons – like the electron, muon, and their neutrinos

  Mesons – like pions, kaons, rho, eta, phi, omega, and others

  Baryons – like the proton, neutron, and heavier cousins (Λ, Σ, Ξ, etc.)

Strange Particles

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- Physicists compared the situation to **chemistry before Mendeleev's Periodic Table**, when many elements were known but there was no system.
- By 1960, particle physics was waiting for its own "Periodic Table" to bring order to the growing **particle zoo**.

The Modern Period (1961-1978)

The Eightfold Way

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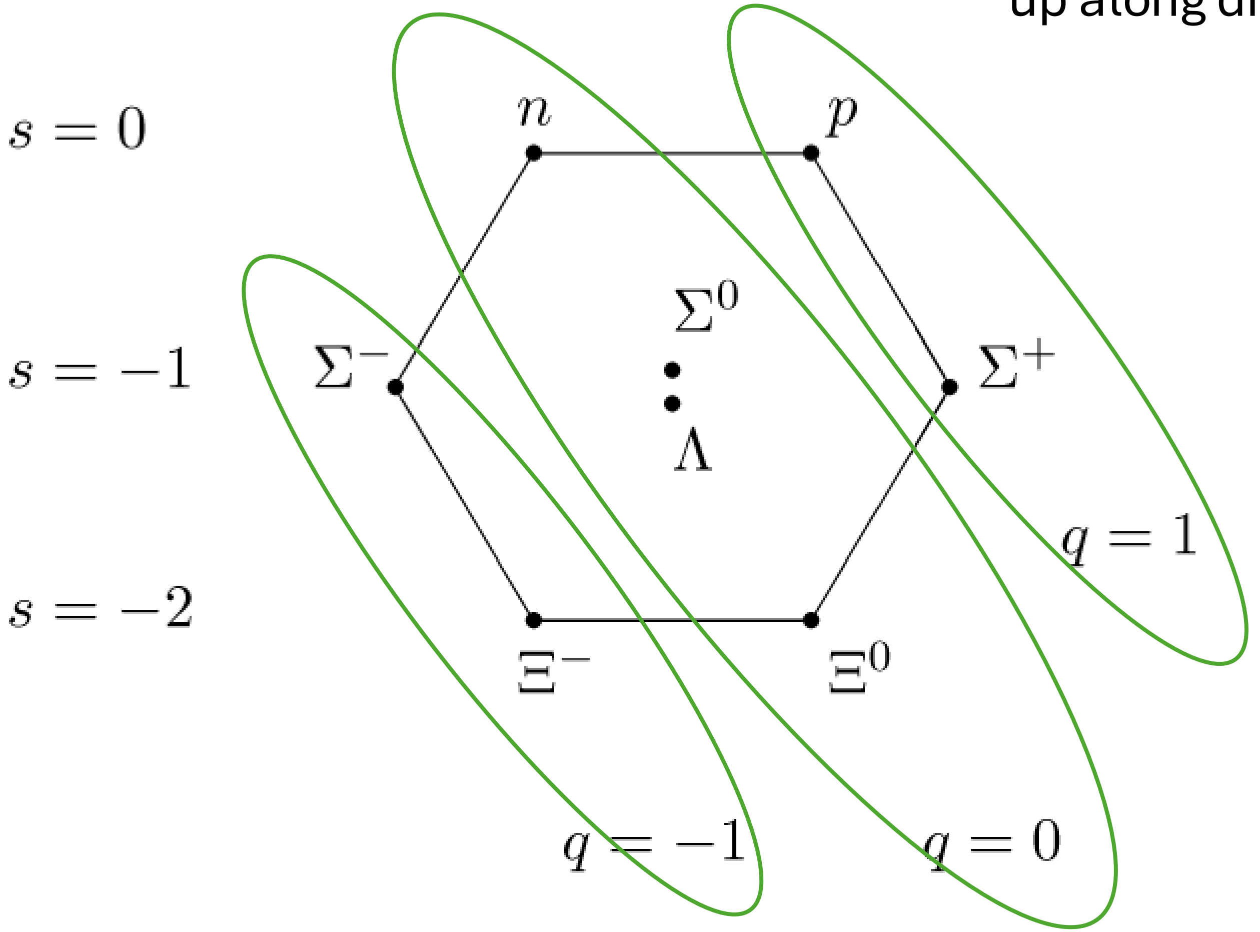
- The Eightfold Way arranged **baryons** and **mesons** into neat geometric patterns, based on two properties:

  Electric charge (Q)

  Strangeness (S)

The Eightfold Way

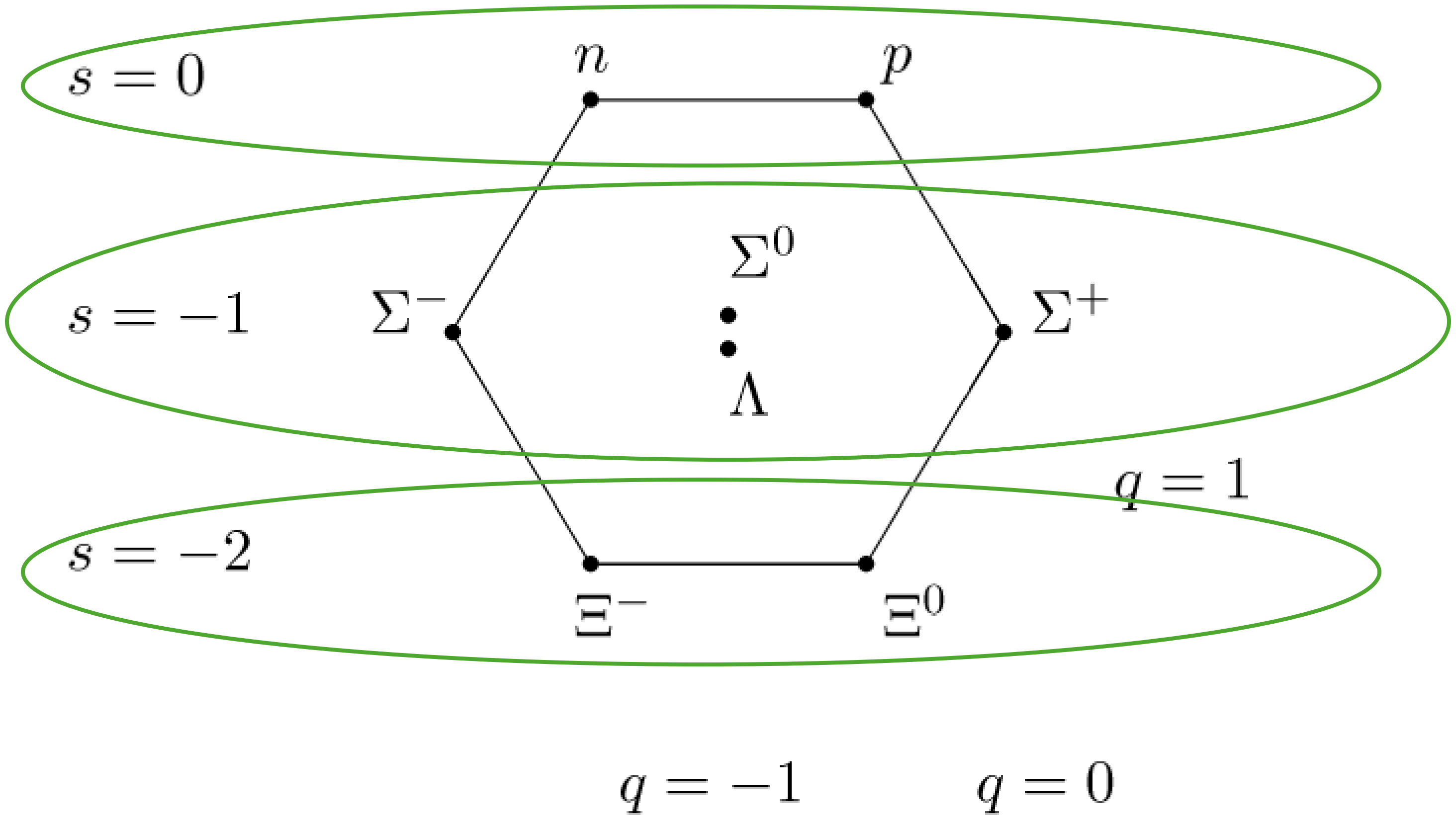
Particles with the same **charge** lined up along diagonals



Source: Wikipedia

The Eightfold Way

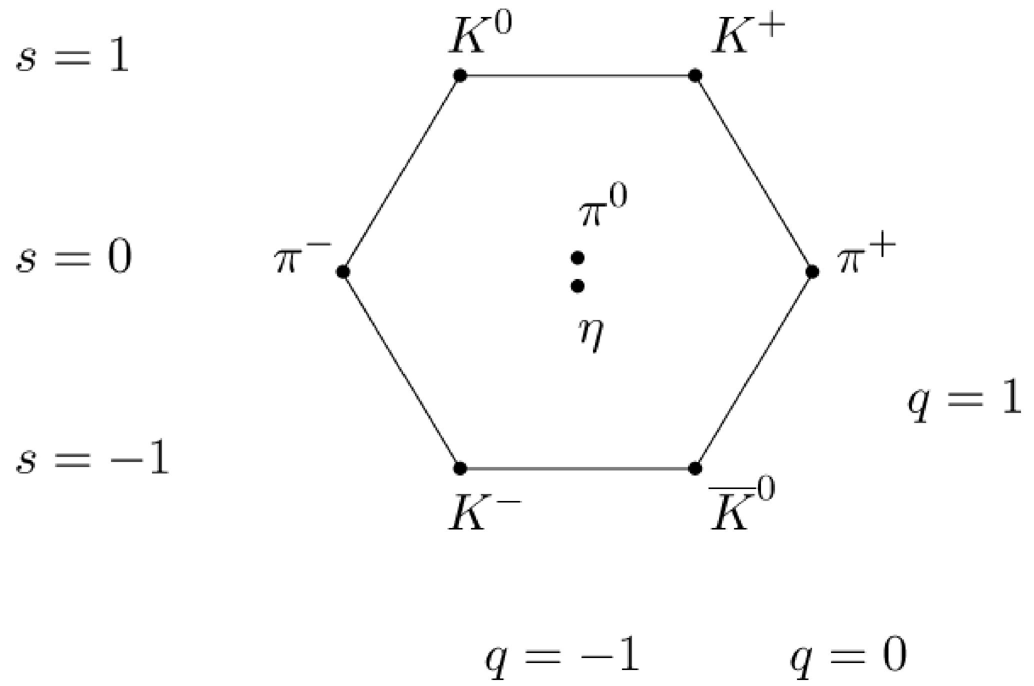
Particles with the same **strangeness** were grouped in horizontal rows



Source: Wikipedia

The Eightfold Way

- The eight lightest mesons fill out a similar hexagonal pattern – the meson octet:



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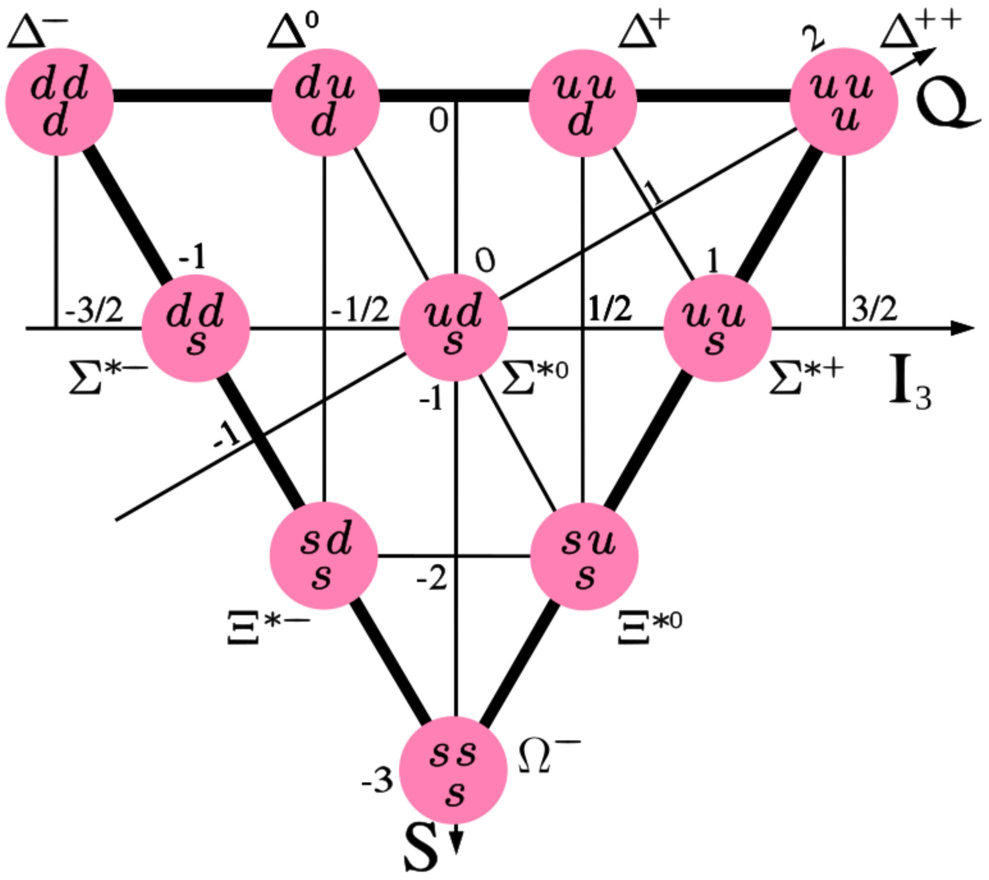
- The **Eightfold Way** didn't just arrange particles into hexagons. It also allowed other shapes, like a **triangle**. One important example is the **baryon decuplet**, which organized **10 heavier baryons** into a triangular pattern.



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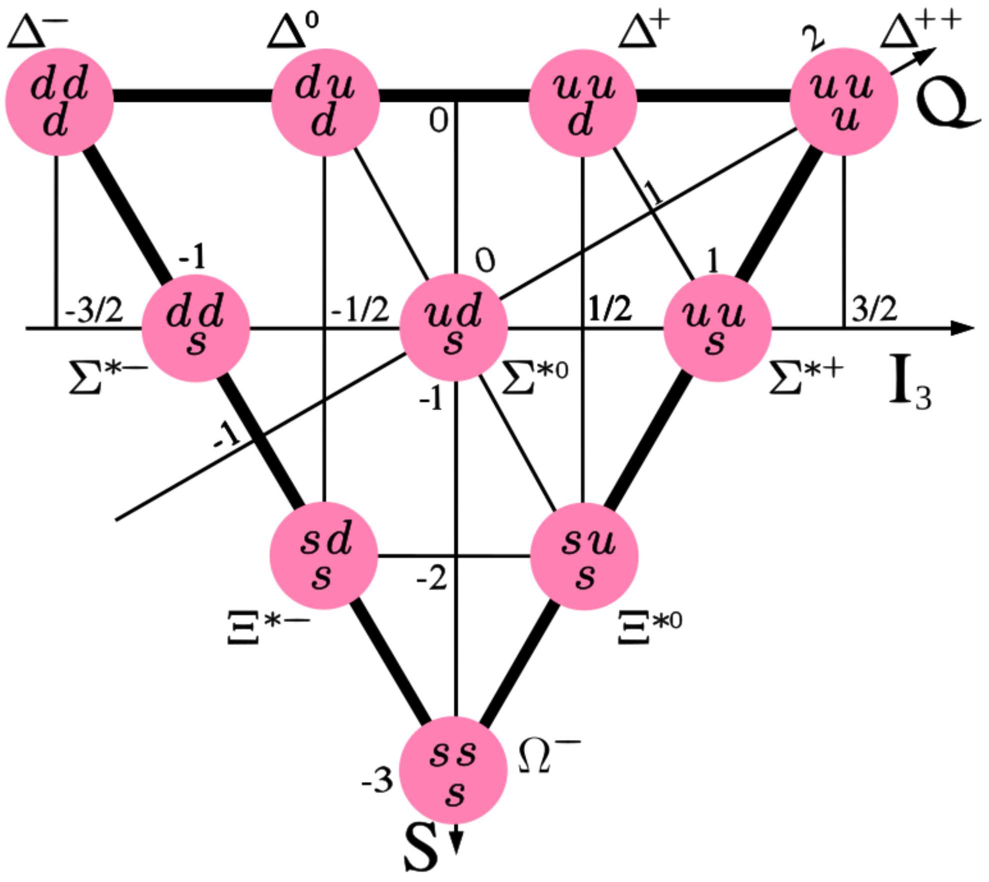
- This arrangement predicted the existence of a missing particle at the tip of the triangle(the **Ω⁻ (Omega minus)**) which was later discovered in 1964, providing strong evidence for Gell-Mann's model.



Source: Wikipedia

The Quark Model

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- The explanation came in 1964, when **Murray Gell-Mann** and **George Zweig** proposed that these particles are not fundamental but instead built from smaller units called **quarks**.

The Quark Model

- There are three basic kinds of quarks (called **flavors**):
  - **up (u):** charge +2/3, strangeness 0
  - **down (d):** charge −1/3, strangeness 0
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- **Mesons** are made of a **quark paired with an antiquark**.
- With this model, the huge variety of baryons and mesons suddenly became understandable: all of them can be explained as different combinations of **u, d, and s quarks**.

The Quark Model

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- But there was a big problem: no one had ever seen a **free quark**. Smashing protons never released quarks directly — instead, new particles (like pions and neutrons) were produced.
- This failure made many physicists doubt the model. To deal with it, they introduced the idea of **quark confinement**: quarks are permanently trapped inside baryons and mesons and can never escape.

The Quark Model

- In 1964, **O. W. Greenberg** suggested that each quark doesn't just have a flavor (up, down, or strange) but also a new property called **color** (red, green, or blue). Antiquarks have the opposite colors.

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- This led to the rule: **all naturally occurring particles must be colorless**.
- Although it first sounded artificial, the **color idea** became the foundation of the modern theory of the strong force, now called **quantum chromodynamics (QCD)**. We will learn more about this later in the course.

The November Revolution

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- What made it so special was its **very long lifetime** about 10^{-20}seconds. That may sound tiny, but for such a heavy meson, it was about **1,000 times longer** than expected.
- This was a huge clue that something new was going on in physics.

The November Revolution

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- They proposed adding a fourth quark for symmetry and the J/ψ discovery confirmed.

The November Revolution

- After that, many more **charmed particles** were discovered, and the quark model was revived with strong evidence.

The November Revolution

But the story continued:

- In **1975**, a new lepton, the **tau (τ)**, was discovered, with its own neutrino. Now there were **six leptons**, but still only **four quarks**.

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- In **1977**, the **upsilon (Υ)** meson was discovered, made of a new quark–antiquark pair, the **bottom (b)** quark.
- That suggested there must also be a **sixth quark**, the **top (t)**, to match the six leptons. The top quark was finally found in **1995**, and it turned out to be incredibly heavy — nearly **200 times the mass of a proton**.

The Standard Model and Beyond the Standard Model (1978- Present)

The Higgs Boson

Higgs Boson

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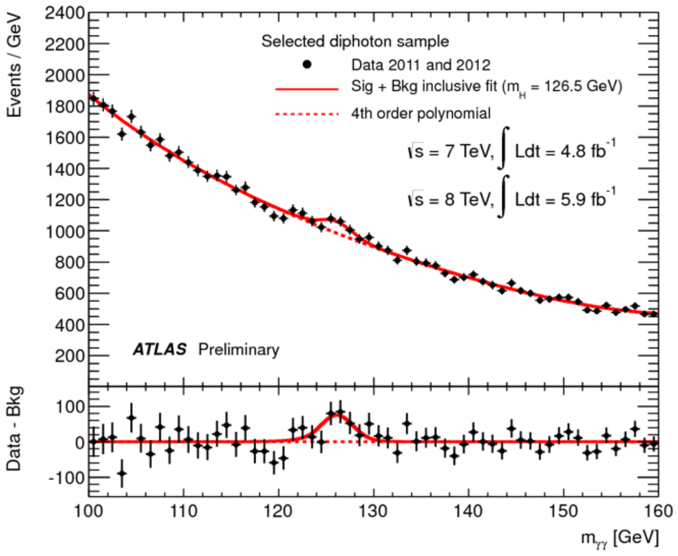
- For years, experiments failed to find the Higgs, so scientists kept adjusting their guesses about its mass, each time pushing it higher.

Higgs Boson

In **July 2012**, the **ATLAS** and **CMS** experiments at CERN's **Large Hadron Collider (LHC)** announced the discovery of the **Higgs boson**. Its measured mass is about **125 GeV**, right in the range where the LHC could find it.



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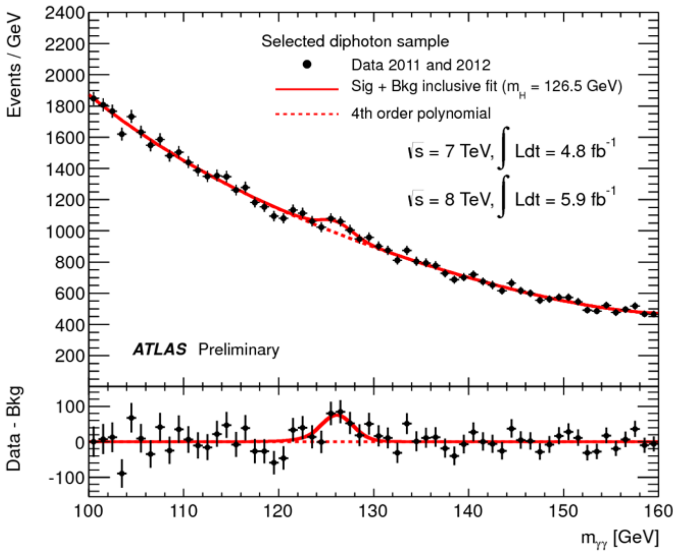
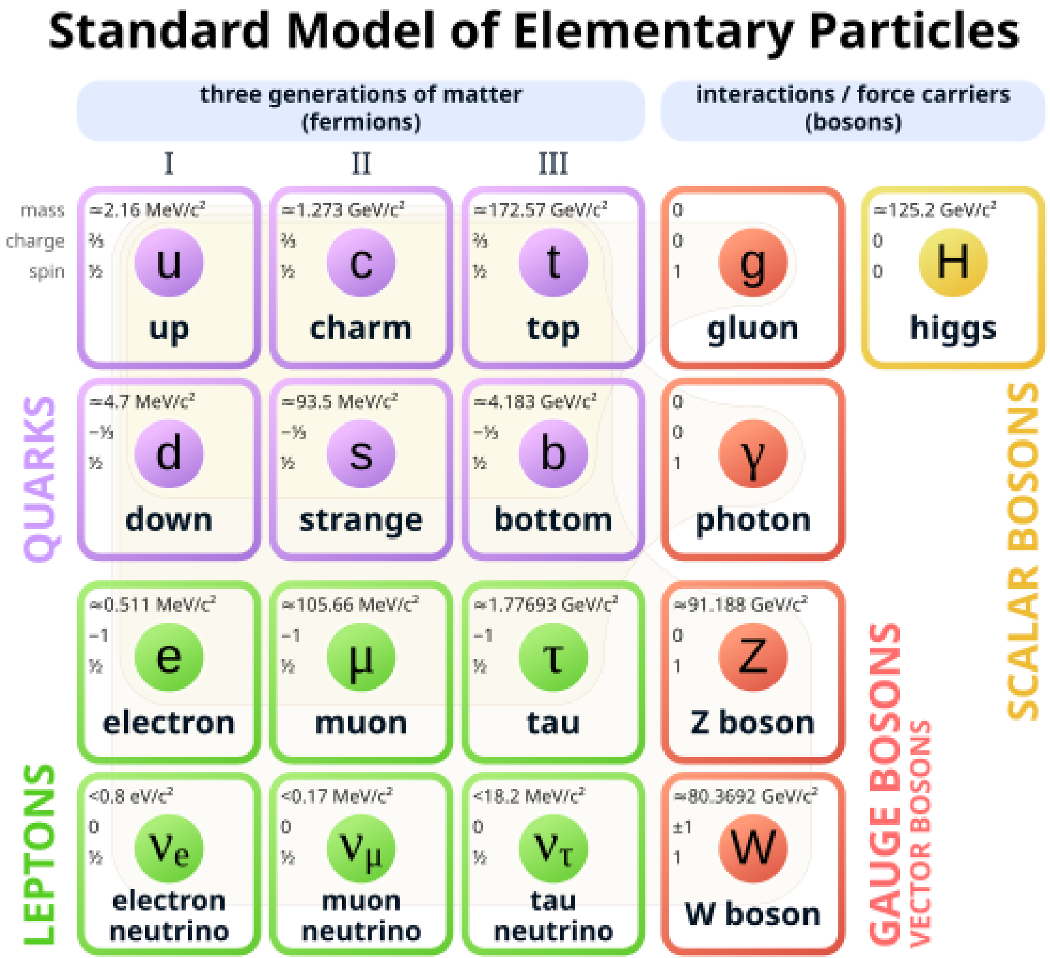


Source: Cern

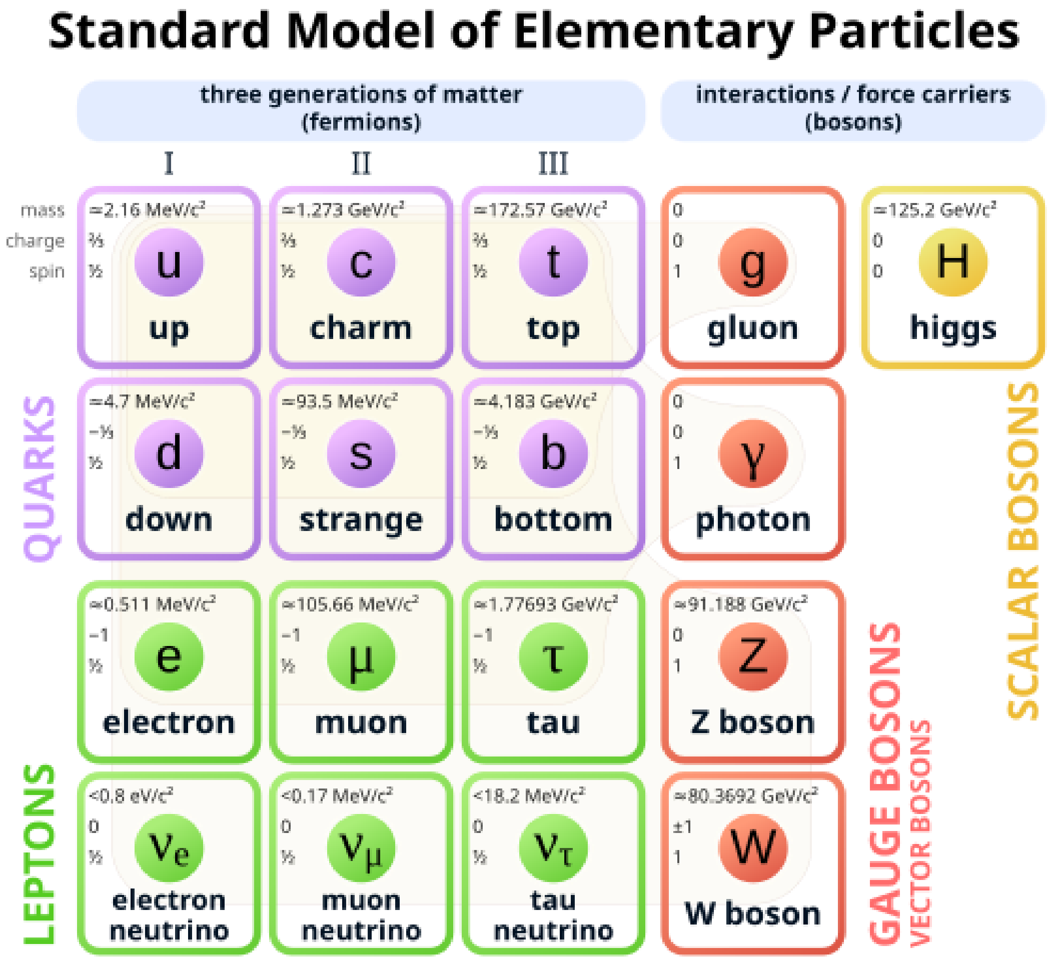
We will learn about Higgs Boson in detail in separate lecture.

The Standard Model



The **Standard Model** says that all matter is made of three basic kinds of particles: **leptons, quarks, and mediators** (force carriers).

The Standard Model



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Finally, the **Higgs boson** acts as the mediator of mass, just like the photon mediates electromagnetic force. Its discovery confirmed the Standard Model.

Beyond the Standard Model

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- **The Higgs Fine Tuning Problem**
- **The Strong CP problem**
- **Any more questions that I am unaware of. We will study these in more detail in later lectures.**

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- **Superstring theory:** Since the 1980s, it has promised a "theory of everything" that unifies quantum mechanics, relativity, and all forces of nature. Whether it can truly succeed is still unknown.

Questions to Think About

1. Is there fourth generation of Particles?
2. How did scientists react when new particles like the electron, proton, neutron, neutrino, and quarks were first proposed, were those proposals well motivated, and what kind of evidence would convince us today if someone suggested a completely new particle?