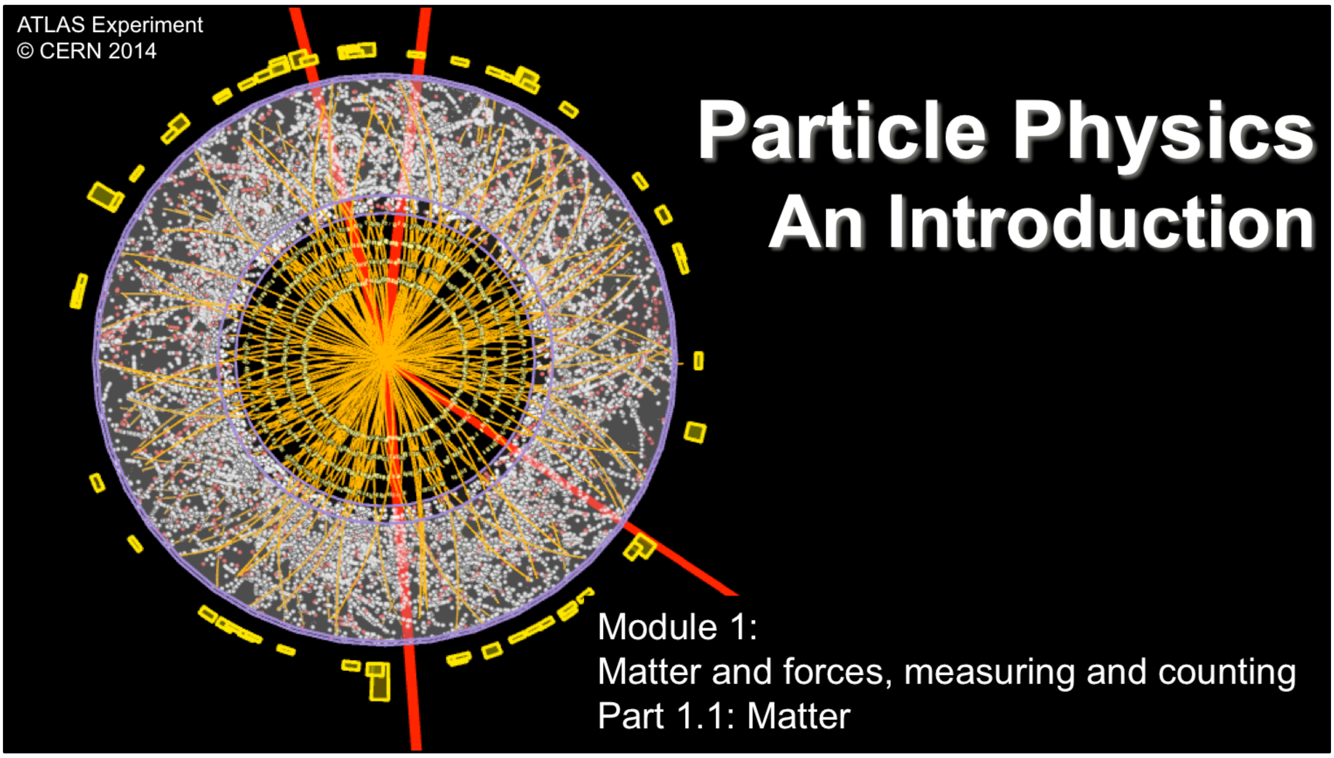


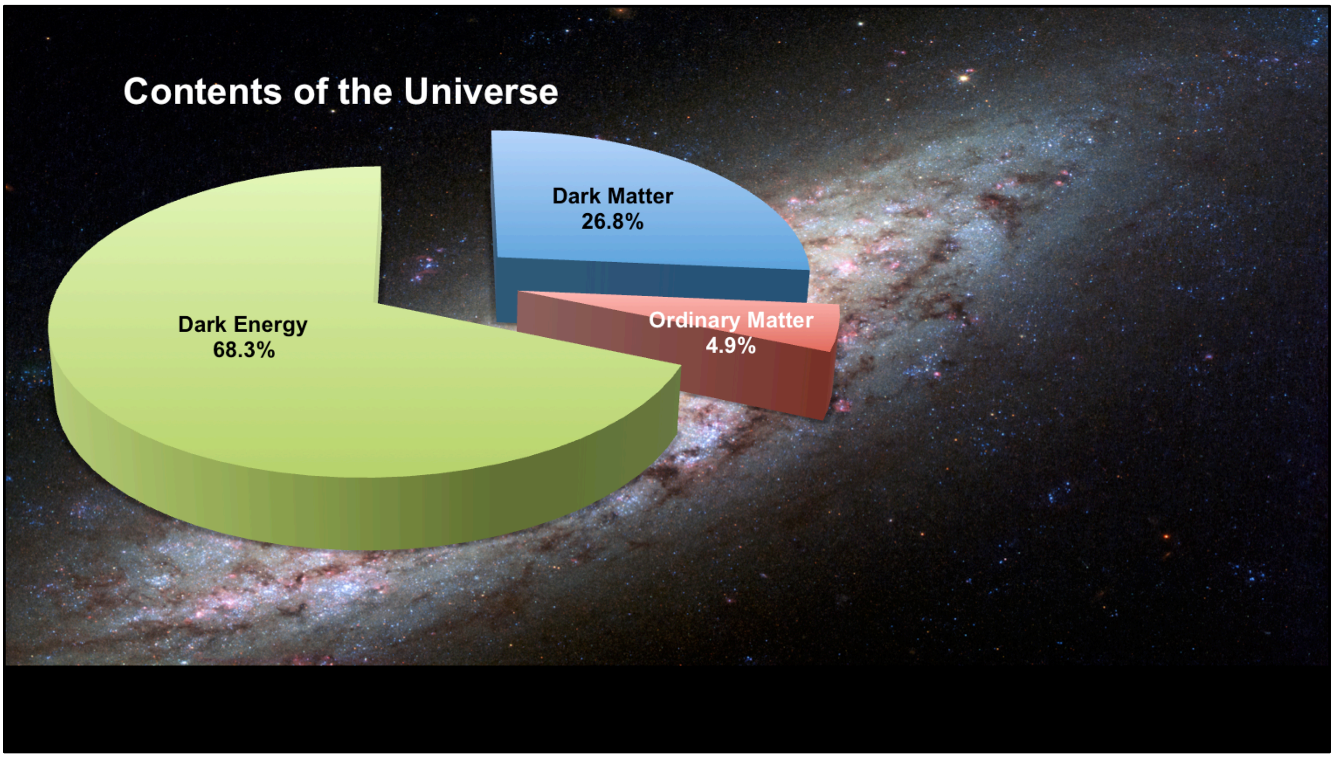
Hello and welcome to this introductory course on subatomic physics, brought to you by University of Geneva.

- During this first module, we will give an overview the objects studied in particle physics, namely matter, forces and space-time.
- We will also discuss how one characterizes the strength of an interaction between particles using the concept of cross section which is central to our subject.
- At the end of the module, we will visit the laboratory of the nuclear physics course at University of Geneva to see an example of how this works in practice.

In this first video we will take a quick tour of matter at the subatomic level.

After having watched this video you should:

- Know quarks and leptons by name and some of their fundamental properties;
- Be able to assign these constituents of matter to families and generations;
- And know the quantum numbers, which are conserved in interactions among particles.



We are interested in the subatomic structure of matter. Here is a schematic picture of the components of an atom. Of course it is not to scale, otherwise the nucleus would be invisible.

- The atom consists of a **positively charged nucleus** of small size, , ~**10^{-14}m,** and a surrounding **electron cloud**, which is 10'000 time larger, ~**10^{-10}m**, and negatively charged.
- For all we know, the **electron** is an elementary particle, without internal structure and probably without size. It belongs to the family of **leptons**.
- Electrons and nucleus are bound together by **the electromagnetic force**.
- The **nucleus**, on the other hand, is not elementary, it contains protons and neutrons bound together by the **nuclear force**. We will talk about the physics of the atomic nucleus in the next module.
- **Protons and neutrons** are not elementary either, they contain **quarks** bound by the **strong force**.
- As far as we can tell today, **quarks are elementary** in the same sense as electrons.

But be careful: All of this describes just about 5% of the Universe! The rest is dark matter and dark energy, we will talk about these in Module 8.

adapted from cpepweb.org

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

	Leptons spin =1/2			**Quarks** spin =1/2			
	Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge	
Neutrinos	ν_L lightest neutrino*	$(0.0001–2)\times10^{-9}$	0	**u** up	0.002	2/3	**Quarks up** **Light Generation**
Charged Leptons	**e** electron	0.000511	–1	**d** down	0.005	–1/3	**Quarks down**
	ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0	**c** charm	1.3	2/3	**Medium Generation**
	μ muon	0.106	–1	**s** strange	0.1	–1/3	
	ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0	**t** top	173	2/3	**Heavy Generation**
	τ tau	1.777	–1	**b** bottom	4.2	–1/3	

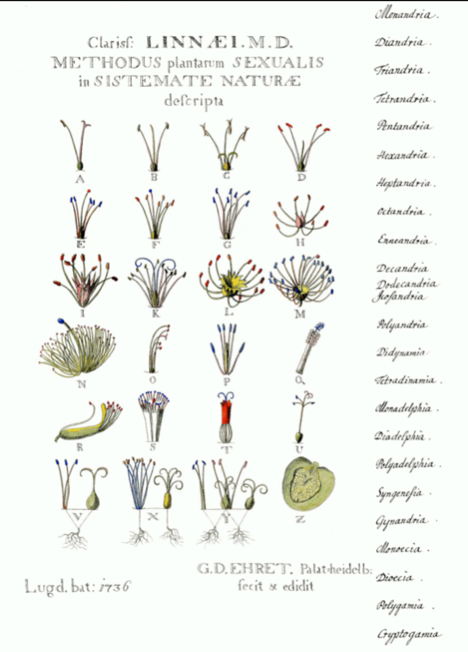
One can assign quarks and leptons to **families** according to their properties, and to **generations** according to their mass, as shown in this table:

- The **lepton families** are shown on the left: all **charged leptons** have similar properties as the electron, which is the most well know member of this family. Their electric charge is minus one elementary charge *e*. The neutral leptons, the **neutrinos**, are produced in radioactive decays. They have zero electric charge and a very small mass.
- The quark families are shown on the right: these are the constituents of proton and neutron, and of all particles called hadrons. There are also two types: the up-type quarks have an electric charge of +2/3*e,* the down-type quarks have charge -1/3*e.*

Every family has **three generations**, almost identical copies of the first one but a lot heavier:
- In the first generation we find the electron e, the light neutrino ν_L and the quarks up u and down d. These are the constituents of the matter around us today.
- The second generation has the muon μ, the medium neutrino ν_M, the charm quark c and the strange quark s.
- And finally in the third generation we find the tau lepton, the heavy neutrino ν_H and the top and bottom quarks, t and b.
- There is a quantum number called **flavor**, which distinguishes between the generations inside each family. It is conserved by all interactions, except the weak interaction.

The **range of masses** in this table is very large:
- Neutrinos are the lightest matter particles, their masses are below 2 eV, probably rather in the range of meV. We will talk more about them in Module 6 which covers weak interactions.
- The top quark has a mass as large as a Hafnium nucleus (*A*=178, *Z*=72), but as far as we know it still is a point-like particle.

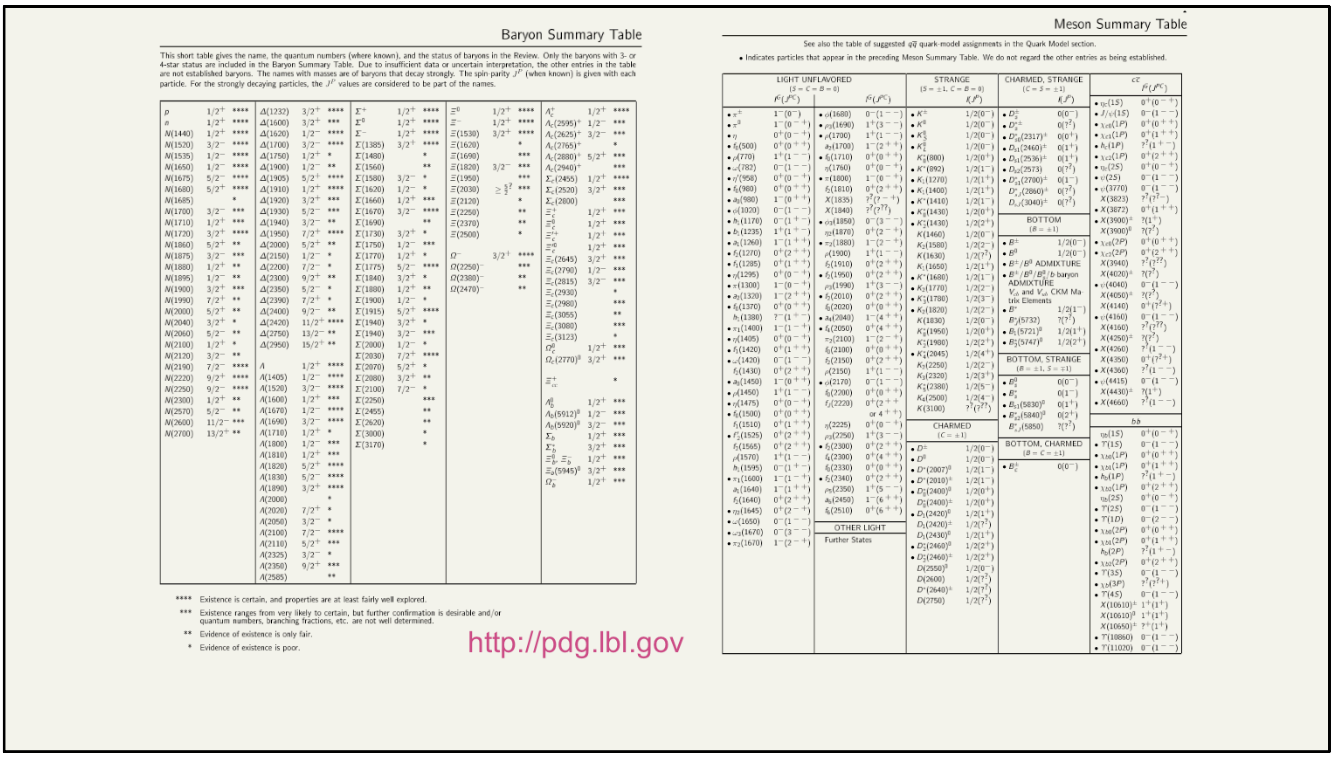
Georg Dionysius Ehret
according to Carl von Linné,
Systema Naturae, 1735



With these constituents, we can implement a descriptive nomenclature **à la Linné**

	Hadrons		Leptons	
	Baryons	Mesons	Charged	Neutral
u, d:	p, n, Δ	π, η, ρ, ω ...	$e^{\pm}$	ν_L
s:	Λ, Σ, Ξ, Ω	K	$\mu^{\pm}$	ν_M
c:	Λ_c, Σ_c, Ξ_c, Ω_c	D, D_s, η_c, J/ψ, χ_c		
b:	Λ_b, Σ_b, Ξ_b, Ω_b	B, B_s, B_c, Υ, χ_b	$\tau^{\pm}$	ν_H
t:	–	–		

- We call **hadrons** all particles which contain quarks; they are sensitive to strong and nuclear interactions, **leptons** are not.
- **Baryons** are bound states formed by 3 quarks, **mesons** contain a quark and an antiquark.
- The **nucleons** p and n are the lightest baryons, they form the atomic nuclei we find around us.
- There are no hadrons including a **top quark** because of its short lifetime. This quark decays before it can form a bound state with others.
- **Leptons** are elementary in the sense that they are not composed of others particles for all we know. Observations are compatible with them having no size. They are pointlike, and so are the quarks.
- You will often see the **neutrinos** ν_e, ν_μ, ν_τ in tables of this sort. These are mixtures of the true particles (with a specific mass) which we denote by ν_L, ν_M, ν_H to identify their mass hierarchy and thus their generation.



- The enormous strength of the strong force binds quarks together to form very stable **bound states**. To be sensitive to the strong force, particles need to have the necessary charge, which is called color. Quarks do have color charge.
- This leads to a whole **zoology of hadrons** as shown in this summary table. The **Particle Data Group** is responsible to collect all the data concerning their properties. An exhaustive list of states as well as all a summary of their known properties is available on their site quoted in red.
- On the left you see a list of **baryons** containing three quarks, like the proton p=(uud), and the neutron n=(udd).
- On the left is a list of **mesons** formed by quark-antiquark pairs, like the π^+=(u,đ).
- Leptons are not sensitive to the strong force because they do not carry the necessary color charge. They interact only via the electromagnetic and weak force and do not form long-lasting bound states among themselves.

	Spin	# bar.	# lept.	Q elec.	T, T_3 weak[1]	C strong
Leptons:						
ν_L, ν_M, ν_H	$1/2$	0	$+1$	0	$1/2, +1/2$	0
e^-, μ^-, τ^-	$1/2$	0	$+1$	-1	$1/2, -1/2$	0
Quarks:						
u, c, t	$1/2$	$+1/3$	0	$+2/3$	$1/2, +1/2$	R, G, B
d, s, b	$1/2$	$+1/3$	0	$-1/3$	$1/2, -1/2$	R, G, B
Gauge Bosons:						
γ	1	0	0	0	0	0
Z, $W^\pm$	1	0	0	$0, \pm 1$	$1, (0, \pm 1)$	0
Gluons	1	0	0	0	0	$C\bar{C}$
Vacuum:						
Higgs	0	0	0	0	0	0

[1] Mind helicities and mixtures!

Here is a table summarizing **some important properties** of elementary particles:

- In the upper half you find constituents of **matter**. Leptons and quarks are **fermions of spin ½**.
- In the lower half you find particles that transmit **forces**. These are **bosons of integer spin**.
- The charges are indicated in units of an **elementary charge**, like the one of the electron in the case of the electric charge.
- The **electric charge** has one component. But the concept of charge is not limited to the electromagnetism.
- The weak charge is called **weak isospin** and has two components. It depends on the orientation of the particle spin with respect to its direction of motion, i.e. on its helicity.
- The strong charge is called **color**, it has three components. We use the abbreviations R(ed)m G(reen) and B(lue) to denote them. Color is a property of quarks, and of gluons, which even carry a color and an anticolor simultaneously.

	Spin	# bar.	# lept.	Q elec.	T, T_3 weak[1]	C strong
Leptons:						
$\bar{\nu}_L, \bar{\nu}_M, \bar{\nu}_H$	$1/2$	0	-1	0	$1/2, -1/2$	0
e^+, μ^+, τ^+	$1/2$	0	-1	$+1$	$1/2, +1/2$	0
Quarks:						
$\bar{u}, \bar{c}, \bar{t}$	$1/2$	$-1/3$	0	$-2/3$	$1/2, -1/2$	$\bar{R}, \bar{G}, \bar{B}$
$\bar{d}, \bar{s}, \bar{b}$	$1/2$	$-1/3$	0	$+1/3$	$1/2, +1/2$	$\bar{R}, \bar{G}, \bar{B}$
Gauge Bosons:						
γ	1	0	0	0	0	0
Z, $W^{\mp}$	1	0	0	$0, \mp 1$	$1, (0, \mp 1)$	0
Gluons	1	0	0	0	0	$\bar{C}C$
Vacuum:						
Higgs	0	0	0	0	0	0

[1] Mind helicities and mixtures!

- For every particle there is an **antiparticle**, which has the same mass but all charges opposite.

- Total baryon number:

$$\#(\text{baryons}) - \#(\text{antibaryons}) = \text{const}$$
$$\#(\text{q}) - \#(\bar{\text{q}}) = \text{const}$$

- Total lepton number:

$$\#(\text{leptons}) - \#(\text{antileptons}) = \text{const}$$
$$\#(l^-, \nu_l) - \#(l^+, \bar{\nu}_l) = \text{const} \; ; \; l = \text{e}, \mu, \tau$$

ν_e, ν_μ, ν_τ are mixed states of the particles ν_L, ν_M, ν_H.

- Charges of all types:

Electric charge Q ; Weak isospin (T, T_3) ; Color $C = (R, G, B)$

- Flavor: conserved by strong and electromagnetic, but not by weak interactions.

Charges are additive quantum numbers. For a system of particles, the total charge is the sum of the charges of its constituents. But there are other additive quantum numbers that are conserved:

- The **total number of baryons**, i.e. the number of baryons minus the number of antibaryons, is conserved. This applies in particular to quarks, which have a baryon number of 1/3.
- The **total lepton number**, i.e. the number of leptons minus the number of antileptons also stays constant in a closed system. To a certain extent that is even true generation by generation, but the neutrinos which show up here , ν_e, ν_μ, ν_τ , are mixtures of the « true » particles ν_L, ν_M, ν_H.
- More important than that, the **charges of all types** are rigorously conserved as far as we know. This evidently concerns the electric charge *Q*, but also the weak isospin (T,T_3) and the color $C=(R,G,B)$.
- The **flavor,** which distinguishes between generations, is a special case: it is conserved by the strong and electromagnetic interactions, but not by the weak one.
- We will define what it exactly means to conserve a quantum number when we discuss Feynman diagrams in part 1.5 of this module and in the optional video 4.1a.

In the next video, we will discuss in more detail the forces which act between matter