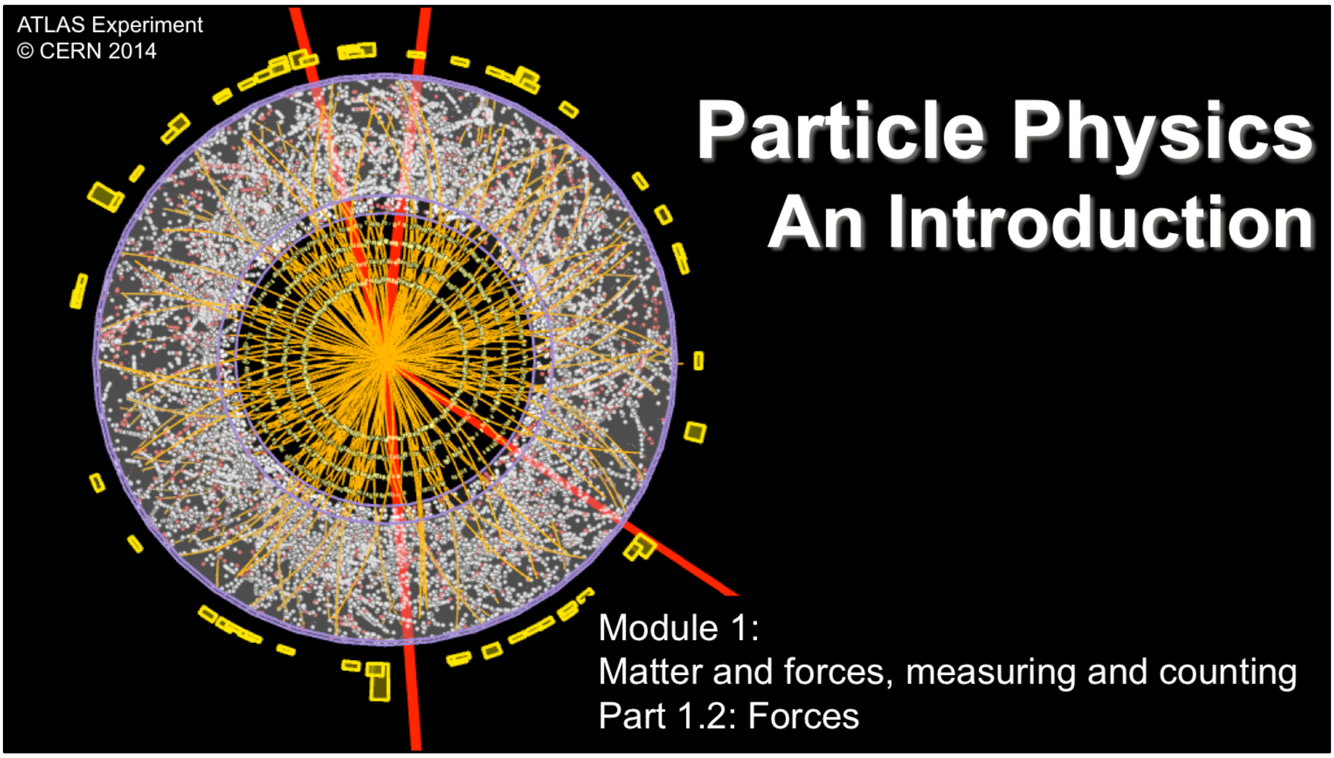


In this first module, we are introducing the objects studied in particle physics, namely matter, forces and space-time.

In this second video we will take a quick tour of the elementary forces and their action at the subatomic level.

After having watched this video you should:

- Be able to name these forces and the associated charges;
- Know the particles which transmit these forces;
- Know the difference between real and virtual particles.

Force	Acts on	Strength	Range	Boson
Strong	Quarks and particles containing quarks	10^4	$\sim 10^{-14}$ m	g
Electromagnetic	Electrically charged particles	10^2	∞	γ
Weak	All particles	10^{-2}	$\sim 10^{-17}$ m	$W^{\pm}, Z$
Gravitational	All particles	10^{-34}	∞	?

Note: strength depends on distance or momentum transfer!

Here is a table comparing elementary interactions. Please note the vast differences between their respective strengths and ranges.

- The **strong force** acts between quarks and particles containing quarks. It has a large strength but a very short range. It is transmitted by gluons.
- The **electromagnetic force** concerns all particles which carry an electric charge. It has a modest strength, but an infinite range. It is transmitted by photons.
- The **weak force** concerns all matter particles. It has a low strength at long distances, but becomes comparable to the electromagnetic force at short distances. It is transmitted by W and Z bosons.
- The **gravitational force** is much weaker than all others, but acts on all particles and has infinite range. Because of the large masses of astronomic objects, it dominates the evolution of the Universe at cosmological scales. It is however negligible at subatomic scales. We do not know how it works at those scales, and we don't even know if it is quantized like the other three forces.

Please note that the strength of all forces depends on **distance**, or equivalently on **momentum transfer**. We will discuss this fact in the context of each force separately, since their distance laws are quite different.

BOSONS force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0		
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

- Forces are transmitted by exchange of **spin 1 bosons:** the photon for electromagnetic interactions, the $W^{\pm}$ and Z bosons for the weak forces and the gluons for the strong force. These bosons are collectively called "**gauge bosons**".
- Particles can emit or absorb such a boson if they carry the required **charge.** To emit a photon, an electric charge is required. But the concept of charge is not limited to electric charge. A particle must have a non-zero weak isospin to emit a W or a Z, and a color charge to emit a gluon.
- The **Higgs boson** is the only entry in this table with **spin 0**. Its role is to keep particles from moving at the speed of light. This applies to all particles, including the Higgs boson itself, with two notable exceptions. One is the photon, which always moves at the speed of light, hence its name. The other one is the gluon, which is however confined to bound states between quarks as we will discuss in Module 5.

How does the transmission of forces via the exchange of particles work? To understand this it is useful to recall how forces act in classical and quantum physics.

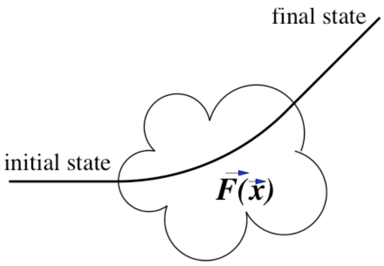
Validity: $v \ll c$
$\Delta x \gg 10^{-10}$m

- Evolution according to Newton's law:

$$m\frac{d^2\vec{x}}{dt^2} = \sum_i \vec{F}_i$$

- Forces and energy derive from a potential:

$$\vec{F} = q\vec{E} \quad ; \quad \vec{E} = -\vec{\nabla}V \quad ; \quad E_{pot} = qV$$



How does classical physics deal with the action of forces?

- Particles are described as **mass points**, their position *x* and momentum *p* can be known with certainty.
- Their motion is a smooth curve in space as a function of time, called a **trajectory.** It is determined by Newton's law, if the vector sum of all forces and initial conditions for position and velocity are known.
- The action of forces is continuous, thus the trajectory is a smooth curve.
- The number of particles is conserved, mass points do not appear nor disappear.
- Field and potential are notions subordinate to the central ones of force and energy. We give here the example of electric force and energy, which are related to the potential as shown.

Mind that this description is not wrong at all, after all it allows you to drive your car. But its validity is limited to **non-relativistic velocities** and distances much larger than the **size of an atom**. To talk about subatomic systems at high energies, we need to go beyond classical physics.

- Probability amplitude:

$$\psi(t, \vec{x})$$

- Probability to find a particle at $(t, \vec{x})$:

$$0 \leq \rho = |\psi|^2 \leq 1$$

- Schrödinger equation:

$$\frac{p^2}{2m} = E \quad \Rightarrow \quad -\frac{1}{2m}\vec{\nabla}^2\psi = i\frac{\partial}{\partial t}\psi$$

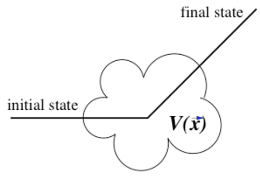
- Interaction with the potentiel, perturbative approach:

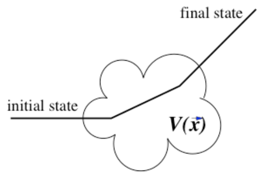
$$i\frac{\partial}{\partial t}\psi + \frac{1}{2m}\vec{\nabla}^2\psi = V\psi$$

- Number of particles conserved:

$$\rho = (\psi^*\psi) \quad ; \quad \vec{j} = -\frac{i}{2m}(\psi^*\vec{\nabla}\psi - \psi\vec{\nabla}\psi^*) \quad ; \quad \partial\rho/\partial t + \vec{\nabla}\vec{j} = 0$$

Validity: $v \ll c$
$\Delta x \lesssim 10^{-10}$m





Quantum mechanics radically changes the approach:

- Particles are field, described by a **probability amplitude** *ψ(t,x)* which is also called a **wave function**. The square of this amplitude $\rho=\psi^2 \geq 0$ gives the probability density to find the particle at *(t,x).* This density is the probability per unit volume.
- The **trajectory** does not exist at small scales, multiple measurements of the position of a particle do not form a smooth curve. Probability amplitude and probability itself evolve starting from an initial state, as described by the **Schrödinger equation**.
- Particles interact with the **potential**. The action of the potential is continuous, but can be approximated by a **perturbative approach**. In this approach, the interaction is implemented as a sequence of point-like interactions. However, the origin of the potential *V* remains unexplained.
- The number of particles is conserved, since the probability amplitude follows a continuity equation, as shown at the bottom of the page. This law relates the local probability density *ρ* to the flux density *j*. If the probability density diminishes at a certain place, $\partial\rho/dt < 0$, there must be divergent flux at the same place, $div(j) > 0$. The flux *j* is thus a flux of probability density.
- The validity of quantum mechanics is limited to **non-relativistic velocities**, since the Schrödinger equation is not covariant, its form depends on the reference frame.

- Relativistic equation of motion:

$$E^2 - \vec{p}^2 = m^2 \quad \Rightarrow \quad -\frac{\partial^2}{\partial t^2}\psi + \vec{\nabla}^2\psi = m^2\psi$$

- Conserved electromagnetic current:

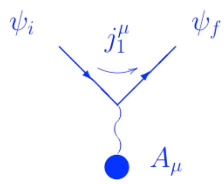
$$j_1^\mu = -2ep^\mu$$

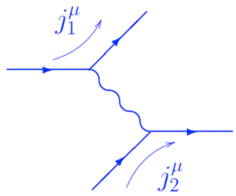
- Potential generated by a second current according to Maxwell's equations:

$$A^\mu = -\frac{1}{q^2} j_2^\mu$$

- Propagator $1/q^2 = (E_\gamma^2 - p_\gamma^2)^{-1}$ describes probability amplitude for the exchange of a photons between the two currents.

Validity: ???





This limitation is overcome by **relativistic field theory**. We are not going to use it in a formal way in this course, but we need its language, its concepts and its results.

- The evolution of particles is described by a relativistic equation of motion, the Klein-Gordon equation, which is manifestly covariant, because it contains only scalars under Lorentz transformation.
- The number of particles is no longer conserved, but the **electromagnetic current density** is. This current is analogous to the probability current, but it is proportional to the charge *e* of the particle. Its conservation means that it is electric charge which is locally conserved, and not the number of particles.
- This gives the possibility to describe the creation of charged particles in **pairs of particle-antiparticle**.
- The potential no longer comes out of nowhere, but it is generated by a second current density j_2 according to Maxwell's laws.
- The four-potential A_μ is generated by the current density j_μ by means of the **propagator** $1/q^2 = (E_\gamma^2 - p_\gamma^2)^{-1}$. This quantity describes the probability amplitude for the exchange of a photon with invariant mass q between the two currents.

- Relativistic equation of motion:

$$E^2 - \vec{p}^2 = m^2 \Rightarrow -\frac{\partial^2}{\partial t^2}\psi + \vec{\nabla}^2\psi = m^2\psi$$

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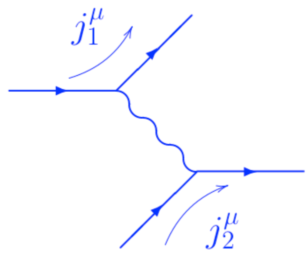

Those who follow carefully may have noticed at least **three unfamiliar notions** in the formulae that come with relativistic field theory:

- The **dimensions** of the quantities do not seam to fit:
  - The first equation relates [energy] = m^2 kg/s^2; [momentum] = m kg/s; and [mass] = kg.
  - Even worse, in the second equation: since [ψ] = 1, the first term has dimension 1/s^2, the second 1/m^2, the third kg^2.
  - The solution to this apparent inconsistency is the use of "**natural units**".
- What do the notations $\boldsymbol{j^\mu}$ and $\boldsymbol{p^\mu}$ mean?
  - This is the notation used for fourvectors, with implicit summation over Greek indices in scalar products.
- And finally, the last equation requires that the **photon has a non-zero mass**.
  - The **real photon** of course has mass 0, after all it moves at the speed of light.
  - The solution is the notion of "virtual particles", which is central to the action of forces in a field theory. Virtual particles have all the same properties as real ones, except that they can have a different mass, which can even be negative or imaginary.

- Mercedes will introduce these three notions one by one in the videos 1.2a, b and c.
- In the next video, we will explain how the probability for a reaction between particless is expressed by what is called the cross section.