The Standard Model of particle physics

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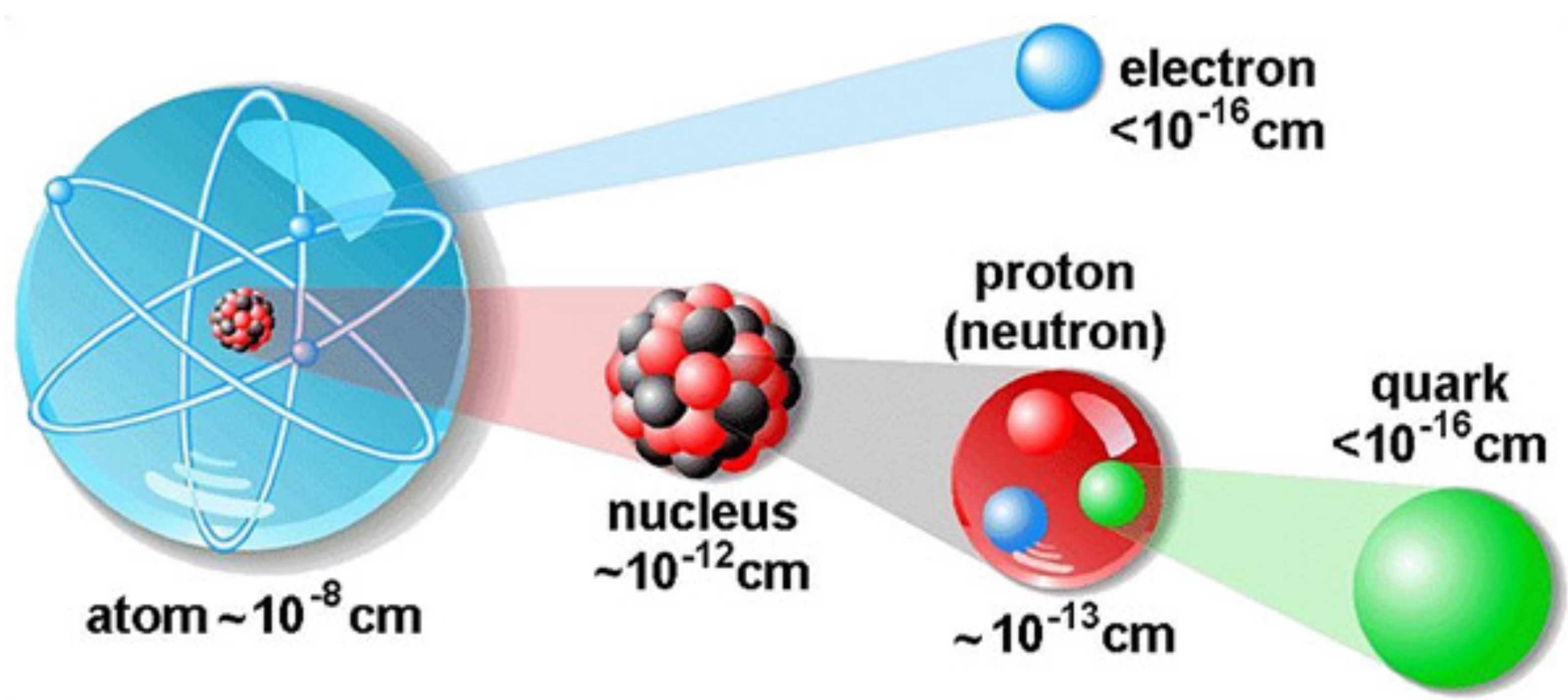
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

- Introduction
- Few concepts
- The electromagnetic interaction (QED)
- The strong interaction
- The weak interaction
- Wrapping up (the Standard Model)
- And now ?

Introduction



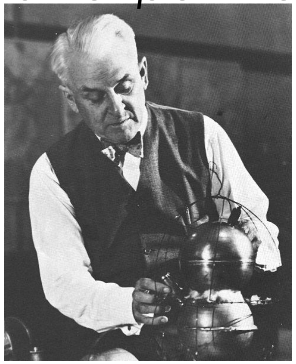
The world we're talking about is a microscopic

Thompson experiment

m/e for electrons

Determination of the nature charge quantum electric of the electron

Millikan experiment



Today

- **e =1.602176462(63) 10^{-19} C**
- **m = 9.10938188(72) 10^{-31} kg**

1 Joule =1Coulomb*1 Volt

1eV = energy acquired by an electron feeling a potential difference of 1 V **1eV = 1.6 10^{-19} Joule**

The world we're talking about is governed by quantum mecanics

$p = h / \lambda$

Particle/Waves

$h = 6.6218 \times 10^{-34}$ Joule sec

The world we're talking about is governed by relativity

$E = mc^2$

Energy/mass

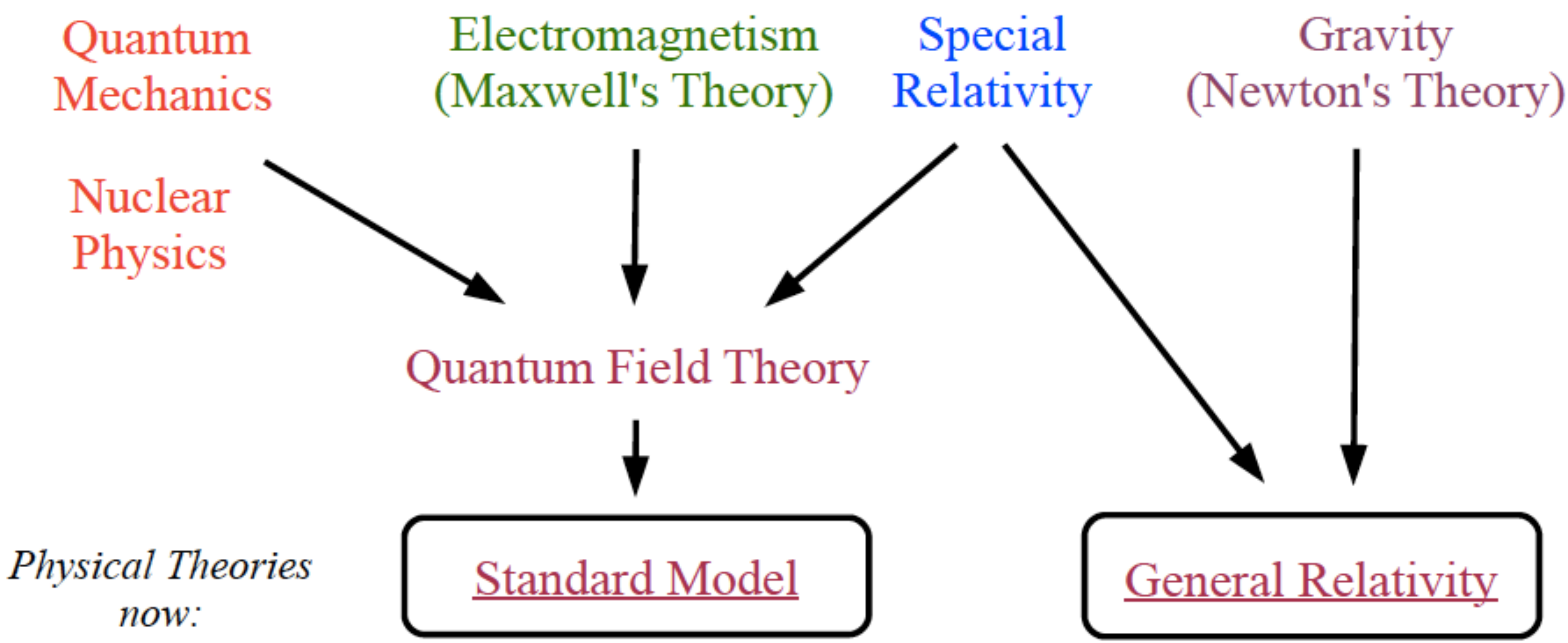
$c = 3 \times 10^8$ m/sec

Probe the underlying structure of matter

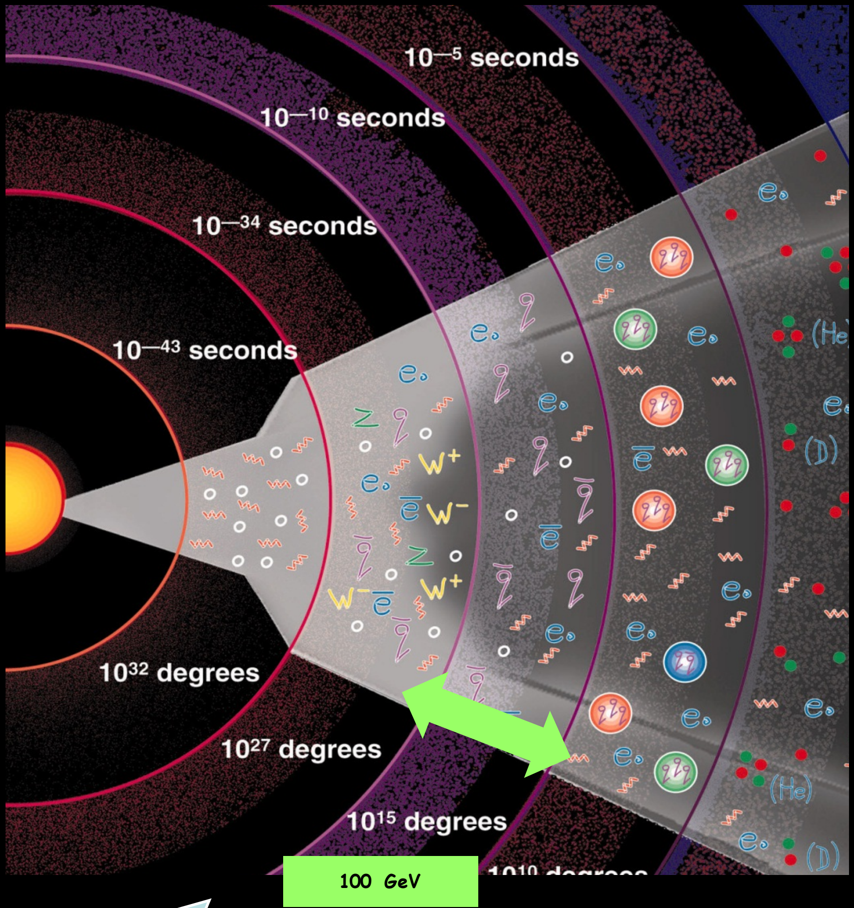
Production of new particles

$p = h/\lambda$
(towards the smallest scales)

$E = Mc^2$
(High energy physics)



The particle world : Physics of the two-infinities



Produce particles at 100GeV ~ 10^{-8} Joule

Temperature ~ 10^{15} degrees

Condition of the Universe after ~10^{-10} sec from Big Bang

<u>Particles (which are very small « objects ») of high energy are instruments to go back in time (very large scales)</u>

From statistical physics

The number of objects having a given potential energy at the thermal equilibrium is given by

$$n = e^{-U/k_B T}$$

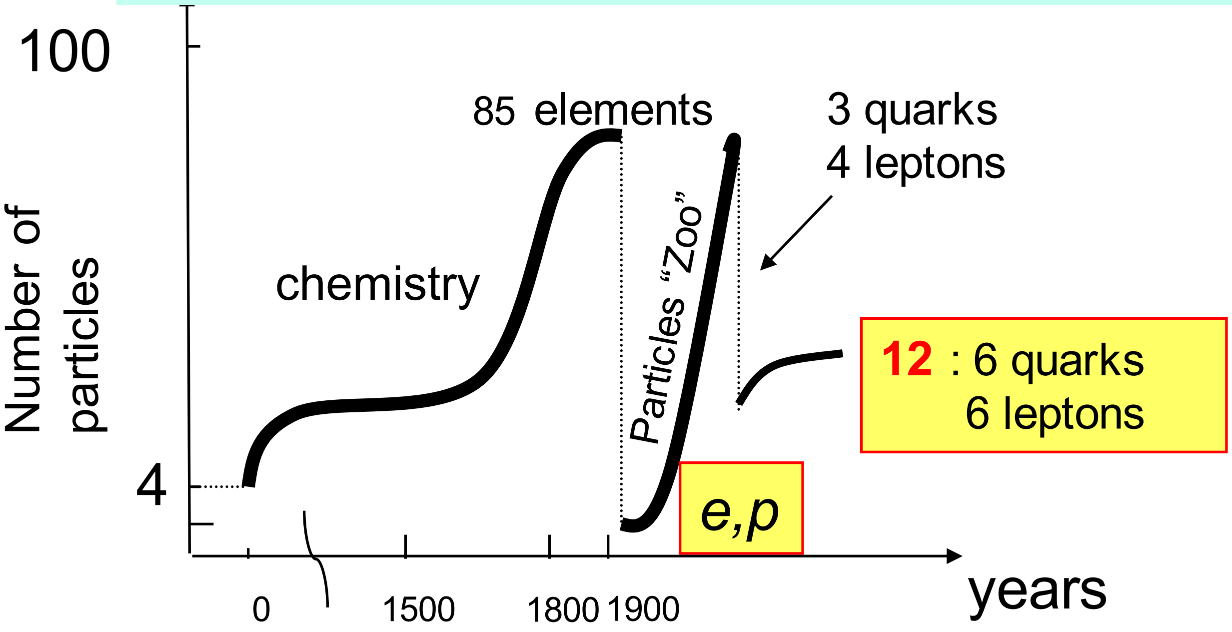
k_B is the proportionality factor linking the temperature and the thermal energy of a system

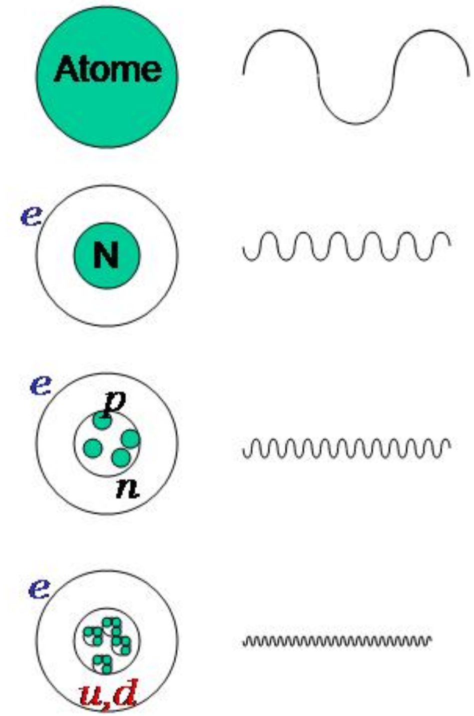
$$k_B = 8.617343 \text{ x } 10^{-5} \text{ eV K}^{-1}$$
$$E_{thermal} = k_B T, \quad k_B \approx 1{,}3806 \times 10^{-23} \text{ JK}^{-1}$$

Remember 1eV = 1.6 10^{-19} Joule

100MeV	T ~ 10^{12} K	10^{-4} sec	after Big Bang
100GeV	T ~ 10^{15} K	10^{-10} sec	after Big Bang

History of Particle Physics in 30 sec…

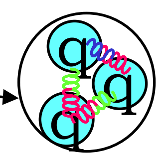




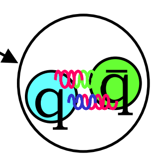
12 matter particles to explain all known particles !

Hadrons : any particle which undergoes the strong interaction

(Nucleon : neutron and proton)



Baryons half integer spin
(ex: p =(uud))



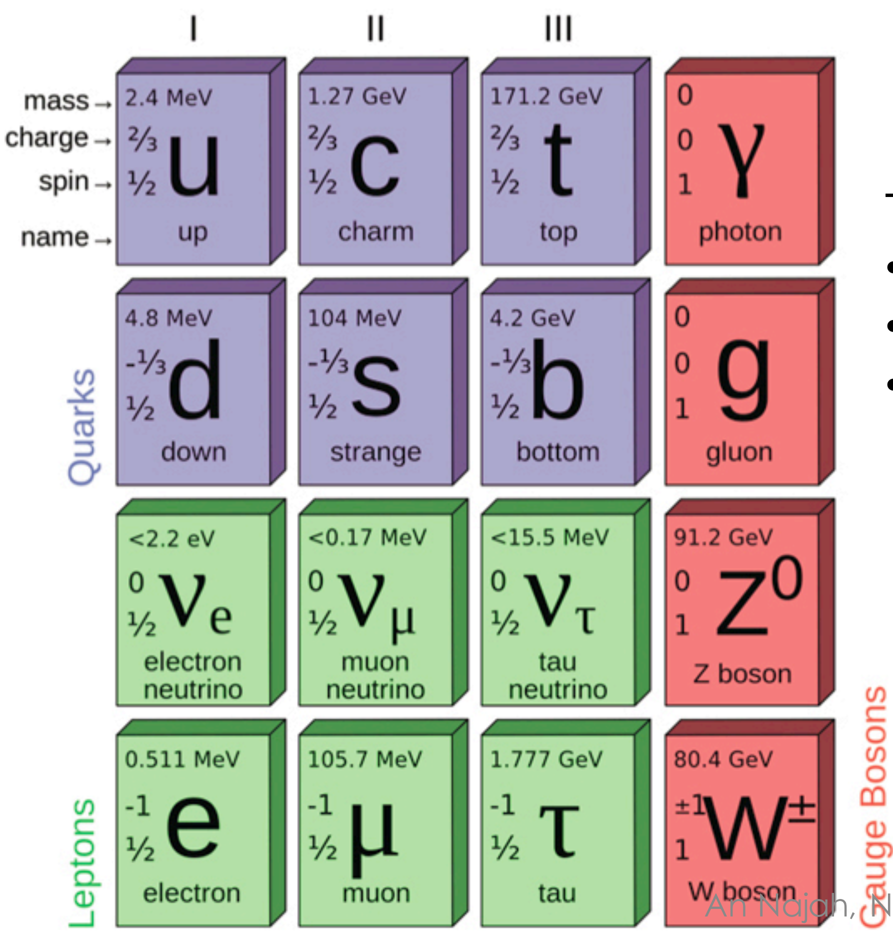
Mesons integer spin
(ex: π = ($u\bar{d}$))

Leptons : Any particle which does not undergo the strong interaction (e,μ,τ) $(\nu_e,\nu_\upsilon,\nu_\tau)$

Elementary particles

3 families of fermions : matter **+ anti-matter !**

3 forces : electromagnetism, weak interaction, strong interaction



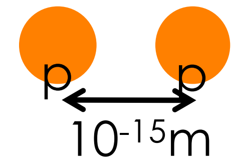
And the **Higgs boson** !

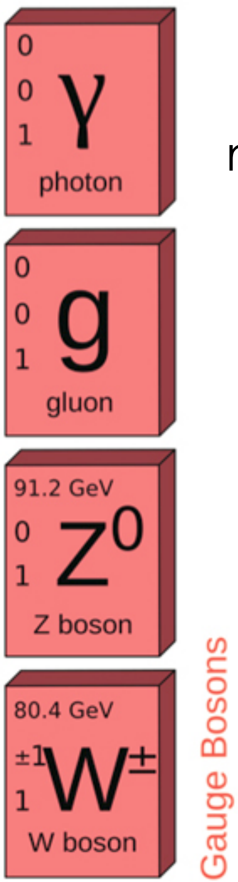
The particles are characterized by :

- their spin
- their mass
- the quantum numbers (charges) determining their interactions

The interactions and their mediators

Spin 1 particles

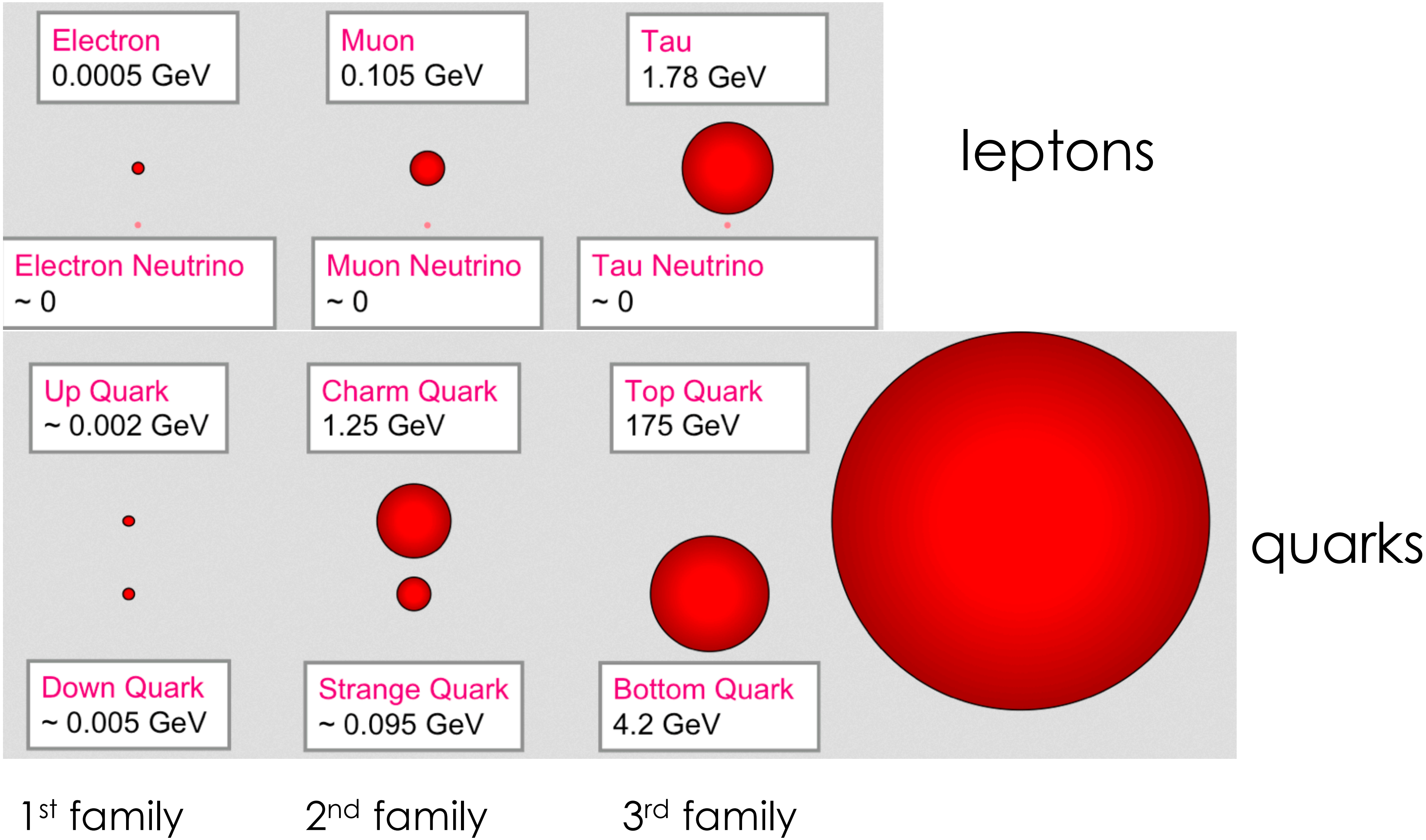




m=0	Electromagnetism	10^{-2}
m=0	Strong interaction	1
m=91.2 GeV M=80.4 GeV	Weak interaction	10^{-8}

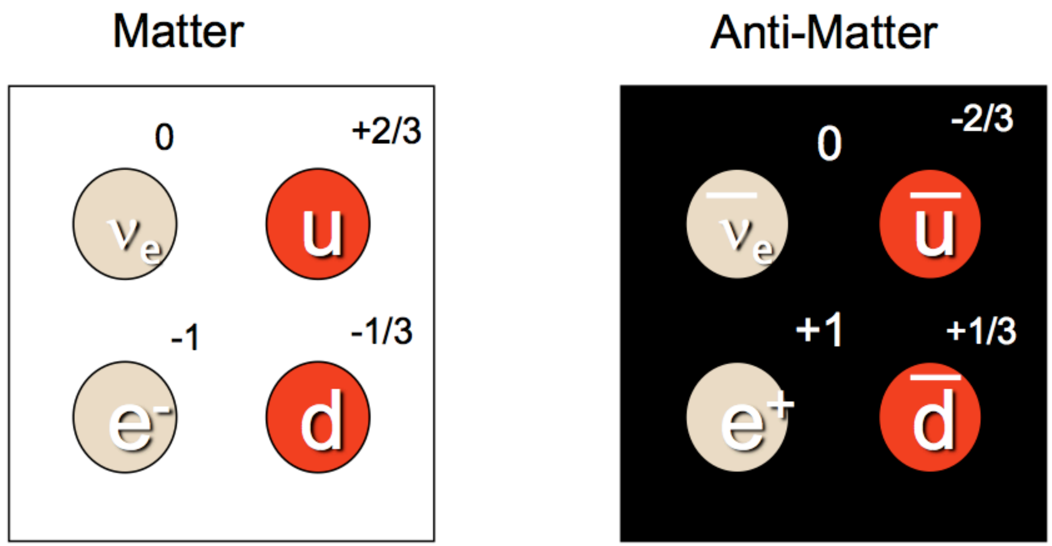
Gravity :
negligible at the scale of elementary particles
We do not know today how to quantify it

The fermions and their masses



Anti-matter ?

To each particle one can associate an anti-particle : same mass but all quantum numbers opposite



In 1931 Dirac predicts the existence of a particle similar to the electron but of charge +e

The Standard Model of particle physics

• built in the last 40 years through interplay between theory and experiment

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

electromagnetism (QED)

Weak interaction

↓

Electroweak interaction

Strong interaction (QCD)

\+ Higgs mechanism

Few concepts

A particle is characterized by :

- its mass
- its spin
- its charges

- its lifetime is a consequence of the above

THE MASS

The mass

Defined by : $m^2c^4=E^2-p^2c^2$ ← Invariant length of the Energy-momentum 4-vector

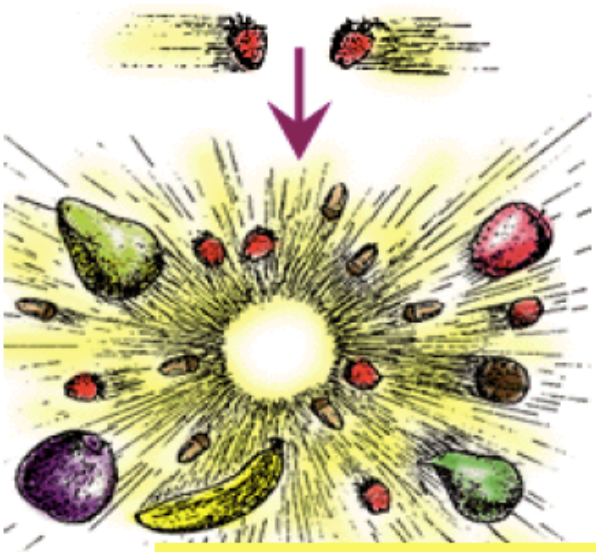
With c=1 E, p and m are expressed using the same unity (GeV/MeV ….)

- When p =0 ⇒ $E = mc^2$
- When v increases ⇒ E^2 et p^2c^2 increase but their difference remains constant
- m is a Lorentz invariant

New particles production:

It is not "divisibility" !

Since c is large
small mass
=
Large energy



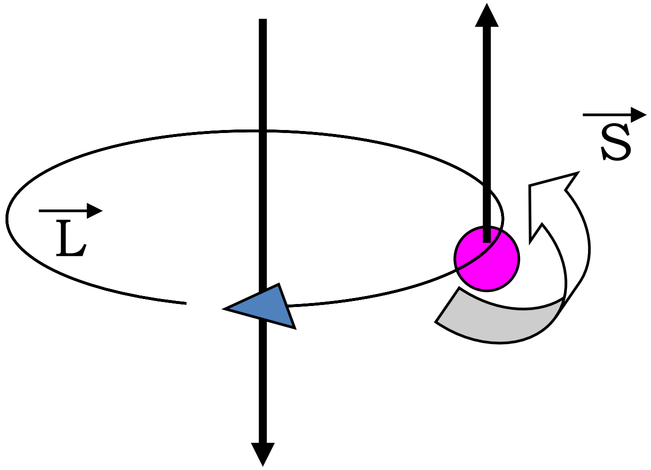
A particle is a lump of energy

Mass/energy

mass	energy
energy	mass

We go back later the mass as an interaction with the Higgs field

THE SPIN



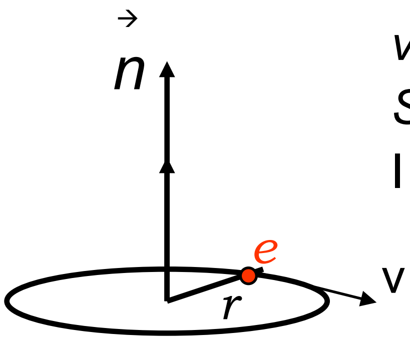
- The spin is the intrinsic kinetic momentum of a particle.
- it can be half-integer
- It determines the behavior of a given particle.
- Few examples of experimental evidences for the spin :
    - **Fine structure of the atoms spectral lines** : each line is made of several components very close in frequency
    - **"Abnormal » Zeeman effect** : Each spectral line is divided in a given number of equidistant lines when the atom is in an uniform magnetic field. «Anomaly» : the atoms of Z odd (ex. Hydrogen) divide into an even number of sub-level. In fact the number of levels is *2l+1* → proof of half integer kinetic momentum !

- The spin has no classical equivalent. Trying to explain it saying that the particle rotates on its own axis does not work.

e,p,n have very different characteristics (charge/ mass/interaction) but they have the same spin : ½

Gyro-magnetic ratio g

- The magnetic moment associated associated to the angular momentum of the electron



n : unity vector
v : electron speed
S : surface
I : intensity = charge / time

$$\vec{\mu} = I\ S\ \vec{n} = \frac{e}{\frac{2\pi r}{v}} \pi r^2 \vec{n} = \frac{e}{2m}(mvr)\vec{n}$$

Quantum angular momentum hl

$$\mu = \mu_B l \quad \text{with} \quad \boxed{\mu_B = \frac{eh}{2m}}$$

Bohr magneton

- Intrinsic magnetic momentum :

$$\vec{\mu} = \mu_B \vec{L}$$

$$\vec{\mu} = g\mu_B \vec{S}$$

spin

gyro-magnetic spin ratio

For fermions (Dirac) elementary particles g=2

The spin obeys the same laws as the other kinetic momenta :

- Algebra similar as the **L** one
- S^2 can have the values $s(s+1)h^2$ (s can be half integer)
- And S_z : mh with $m = -s, -s+1, \ldots -1, 0, 1, \ldots., s-1, s$
- One can add a spin with
  - An other spin ($S = S_1 \oplus S_2$)
  - With an total angular momentum ($J = L \oplus S$)

A particle can have any angular momentum *L* but its spin *S* is fixed

	integer spin (Bosons)		Half integer spin (Fermions)	
	spin 0	spin 1	spin 1/2	spin 3/2
Elementary	Higgs boson	Vectors of the interactions	quarks, leptons	-
Composite	pseudo-scalar mesons (p,K..)	Vector mesons (r,K*)	some baryons (octet)	some baryons (decuplet)

spin/statistics theorem (Pauli 1940)

Bohr and Pauli

Pauli's exclusion principle *: two particles of half integer spin (fermions) cannot be simultaneously in the same quantum state*

Pauli's principle ⟷ anti-symmetry of the wave function by the exchange of 2 particles (for the fermions)

For 2 particles one in the state ψ_a, the other one in the state ψ_b, one can write :

$$\psi(1,2) = \frac{1}{\sqrt{2}}\left(\psi_\alpha(1)\psi_\beta(2) + \psi_\beta(1)\psi_\alpha(2)\right)$$ Symmetric (bosons)

$$\psi(1,2) = \frac{1}{\sqrt{2}}\left(\psi_\alpha(1)\psi_\beta(2) - \psi_\beta(1)\psi_\alpha(2)\right)$$ Anti-symmetric (fermions)

If 2 fermions are in the same state ($\alpha = \beta$) their wave function is 0 ! This problem does not exist for bosons which can occupy the same state (ex. supra-conductors).

This can be generalized for a larger system of particles.

Helicity

- Particle of spin $\vec{S}$
- Direction of the momentum $\vec{n} = \frac{\vec{p}}{p}$
- Helicity :

$$\Lambda = \vec{n} \cdot \vec{J} = \vec{n} \cdot (\vec{L} + \vec{S}) = \vec{n} \cdot \vec{S} \quad \text{since} \quad \vec{p} \cdot \vec{L} = \vec{p} \cdot (\vec{r} \wedge \vec{p}) = \vec{0}$$

- $2S + 1$ eigenvalues of $\Lambda : -S \leq \lambda \leq +S$