Introduction to Particle Physics

Swedish Teachers program 2019

Lecture I

Program

- Lecture I
  - Exploring the particle physics world
- Lecture II
  - Introduction to the Standard Model (SM)
- Lecture III
  - Beyond the SM

Lecture I
Exploring the particle physics world

- Introduction
- Foundations of Quantum Mechanics;
- Fundamental particles, interactions and the quark-gluon plasma

Introduction

- Particle Physics is the study of :
  - the fundamental constituents of the matter;
  - and the forces (interactions) acting among them;

- Purpose
  - provide some help for a unified view of the Universe

- Disclaimer
  - The discussion level of the subject will be mostly qualitative and descriptive, suitable for an introductory course!

Newtonian mechanics

For a macroscopic body of mass m, the Newtonian mechanics

$$\vec{F} = m\vec{a} \Longrightarrow \vec{r} = \vec{r}(t)$$

permit to find $\vec{r}(t)$, *the trajectory of the body in the* *space* *and* *time*:

What an elementary particle is?

- Our sensory experience would lead us to say it has a defined shape and size and therefore localized in the space, something like spheres, with radius, mass and charge;

- Experiments have shown that our extrapolated sensory picture of the basic constituents of the matter is erroneous!!

- The description of the particle propagation in the space-time requires:
  - the Quantum Mechanics (QM);
  - Special Relativity where $E^2 = m^2 + \vec{p}^2$ $(c = 1)$ helds.

Experimental facts claiming the QM

- 1900 M. Plank: black body radiation, energy emitted/absorbed in quanta $E = h\upsilon$ (h, quantum of Action). Atom energy quantized;
  - 1902 P. von Lenard: photoelectric effect (dependence on ν not I)
  - 1905 A. Einstein: Photoelectric effect interpreted as : light is emitted/absorbed in quanta $E = h\upsilon$ (later named photon);
- 1920 ..Compton: photon-electron scattering, photon as a particle p=E/c
- 1927- Germer, Thomson..: Diffraction of electrons trough crystal poudre, electrons behaves as waves;

Experimental facts claiming the QM

So particle (E,p) and wave (ν,λ) variables are linked via h.

$E=h\nu$ and **$p=h/\lambda$**

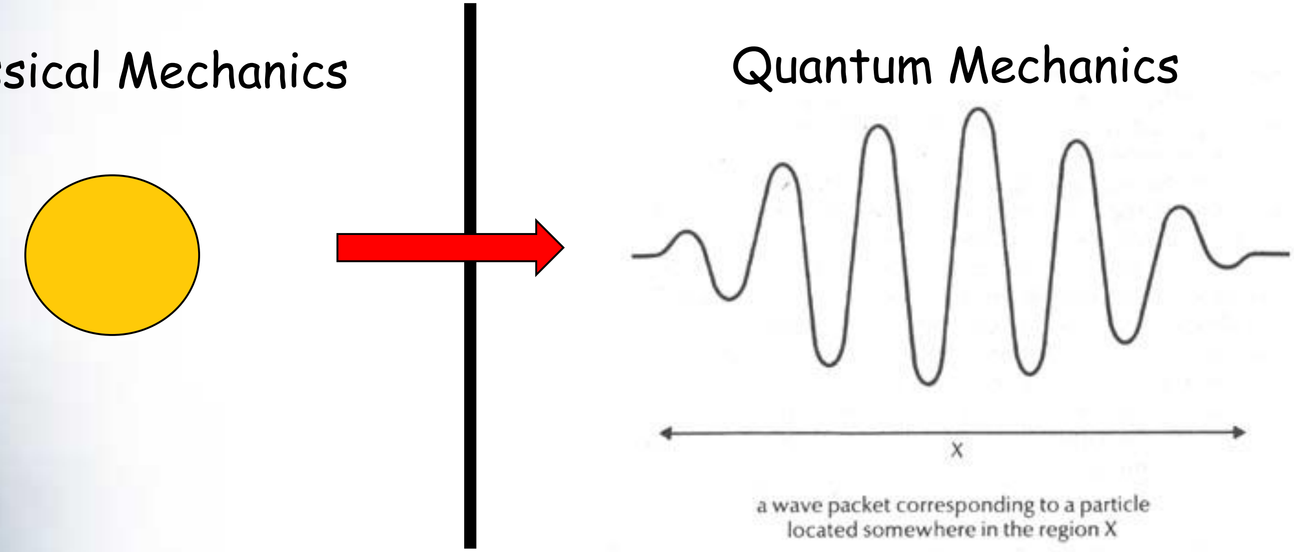
Particle-wave Duality!

Foundations of Quantum Mechanics

The particle view in:

Classical Mechanics

Quantum Mechanics



A particle is a mass field with amplitude appreciably different from zero there where the particle is located.

Heisenberg's uncertainty principle

The Heisenberg's uncertainty principle is a pillar of QM:

$$\Delta x \Delta p \geq h$$

- *It is impossible to know simultaneously and with exactness both the position and the momentum of a particle;*
- *The relation $\Delta E \Delta t \geq h$ also held;*
- *The relation on the angular momentum $\Delta L_x \Delta L_y \geq \frac{1}{2} \hbar L_x$ also held ;*

This principle is a fundamental fact of the nature!

Its interpretation not unanimous! Limit in the knowledge of the nature? Limit in the precisions of the measurements?

Again, what a fundamental particle is?

- An object with particle-wave behaviour (duality principle);
- The Heisenberg's incertitude principle and the minimum quanta of action $\hbar$ imposes
- the QM for the description of the time evolution of a particle imposes,
- Classical mechanics becomes inadequate!

Special Relativity (SR)

Postulates:

1. It is not possible to distinguish by any experiment the relative motion of two inertial reference systems. E.g.: The formulations of the mechanics and Maxwell equations (EM) have to be equivalent in all the inertial reference systems;

2. The velocity of light c in the vacuum is the limit (~3 10^5 Km/s) and it is invariant (the same value) in all the inertial reference systems;

Lorentz transformation and Energy-mass relation

For the invariance of the mechanics the space-time coordinates must transform according to the Lorentz transformation (Lorentz Invariance: LI):

Lorentz Transformation,

From O to O', i.e., $x, y, z, t \rightarrow x', y', z', t'$

$$x' = \frac{x - ut}{\sqrt{1 - u^2/c^2}}$$

$$y' = y$$

$$z' = z$$

$$t' = \frac{t - (u/c^2)x}{\sqrt{1 - u^2/c^2}}$$

New relation Energy-mass

$$E^2 = p^2c^2 + m^2c^4$$

1) Time dilation, space contraction

2) Modification of Newton's laws

3) From space and time to the 4-dimensional space-time of Minkowski

QM: Propagation of a particle

Schrödinger's equation (1926) **is non-relativistic**
(cannot account for creation/annihilation of particles)

Schrödinger Equation (1926): $\left(i\hbar\frac{\partial}{\partial t}+\frac{\hbar^2}{2m}\Delta - V\right)\Phi = 0$

$E=\frac{p^2}{2m}+V$ classical ↔ quantum correspondance $E\to i\hbar\frac{\partial}{\partial t}$ & $p\to i\hbar\frac{\partial}{\partial x}$

SR

Dirac Equation (1928): $\left(i\gamma^\mu\partial_\mu - \frac{mc}{\hbar}\right)\Psi = 0$

$E = \begin{cases} +\sqrt{p^2c^2+m^2c^4} & \text{matter} \\ -\sqrt{p^2c^2+m^2c^4} & \text{antimatter} \end{cases}$

$E=\vec{\alpha}\vec{p}c+\beta mc^2$

$\gamma^0=\beta,\ \gamma^i=\beta\alpha^i,\ \{\gamma^\mu,\gamma^\nu\}=2\eta^{\mu\nu}$

positron (e^+) discovered by C. Anderson in 1932

Christophe Grojean BSM 11 CERN, July 2015

Due to the minimum quanta of action h and ΔxΔp≥h, the particle trajectory is questioned and maybe it looses its meaning.

$|\Phi|^2$ $|\Psi|^2$ (Φ and Ψ wave-functions, solutions of the differential equations) are interpreted as probability density to find the particle in a point p(x,y,z,t).

Ψ is a 4-vector, for particle with spin ½ and with positive and negative energies.

Fundamental particles, interactions and the quark-gluon plasma

Fundamental Components of the matter: quarks and leptons

Quarks

- Jumping over 60 years of history of particle physics and discoveries, to put some order in the particle zoo (hundreds of particles observed), a static quark model was proposed during 1960s ;

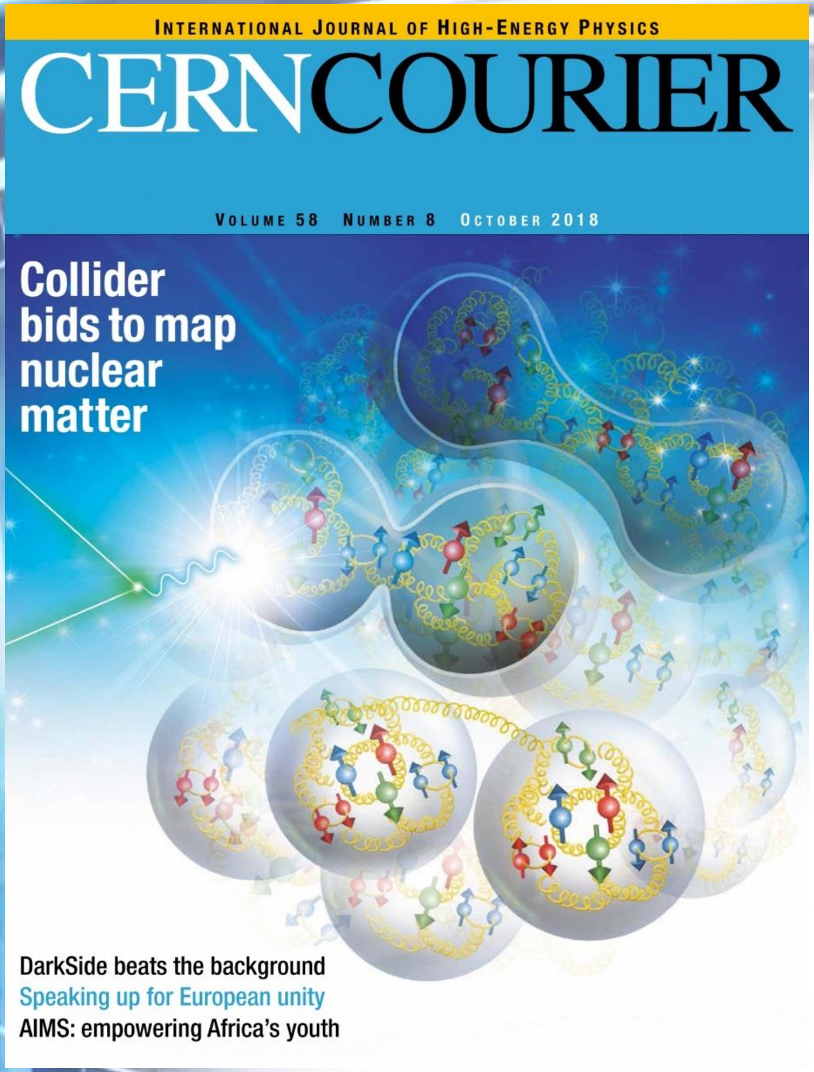
- It was accepted in 1970s after experiments on electron-proton/neutron scattering were carried out. Parton evidence!

- Quarks are fermions with intrinsic angular momentum, $\text{spin} = \frac{(2n+1)}{2}\hbar \quad n = 0,1,\ldots$

Fundamental Components of the matter: quarks and leptons

Quarks

- They have a fractional (!) electric charge, strong and weak charges;
- Quarks are sensitive to the Strong, Weak and EM interactions;
- They are arranged in three families. (up, down), (charm, strange), (top, bottom);
- They are confined in Hadrons and cannot be observed as free particles;



- Quarks have different colors which represent the strong charges: :R,G and B;
- different Kinematic status of quarks (angular momentum and energy levels) result in particles, resonances, with different total energy, then masses;
- Moreover, deeper-inelastic scattering e-nucleons showed the existence of the quark sea and gluons. Last ones interpreted as the mediators of SI.

Fundamental Components of the matter: quarks and leptons

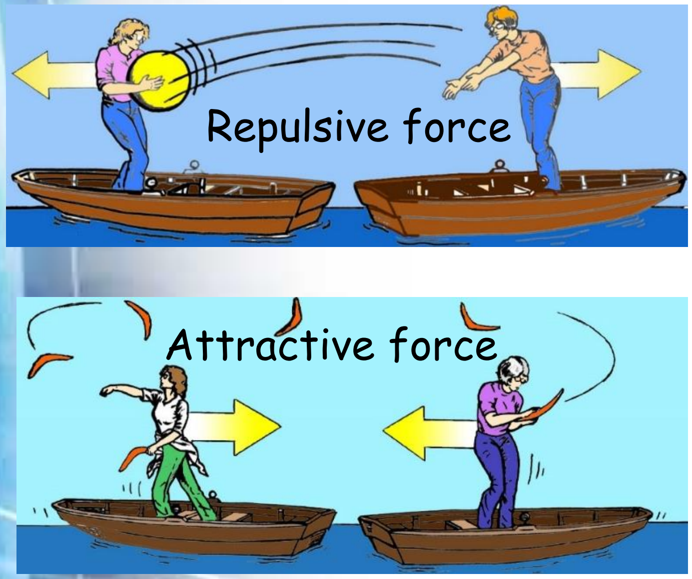
Leptons

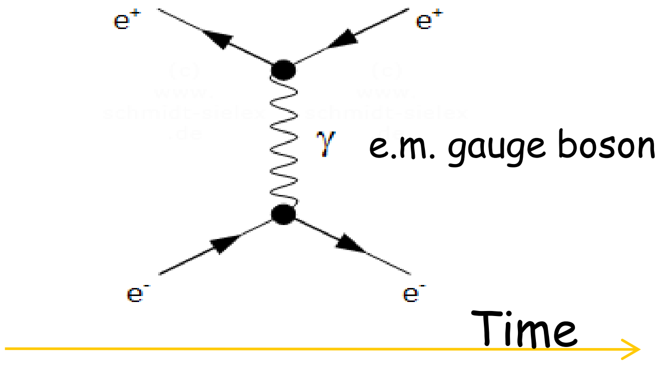
- leptons are fermions with intrinsic angular momentum, spin $\frac{(2n+1)}{2}\hbar \quad n = 0,1,\ldots$
- They have an integer electric charge and weak charges;
- Leptons are sensitive to the Weak and EM interactions. Not to the SI!
- They are arranged in three families and can be observed free;
- electron, muon, tau and corresponding neutrinos are leptons;

Lepton and quarks are the fundamental components of the ordinary matter we are made of!

Paradigm of Fundamental interactions

- Interactions between particles are described by the exchange of interaction mediator known as **gauge bosons** (1947, Lamb and Retherford experiment. See Lect II.);
- Bosons have intrinsic angular momentum $s = \mathrm{n}\hbar, \;\; \mathrm{n} = 1, \ldots)$





Electromagnetic interaction

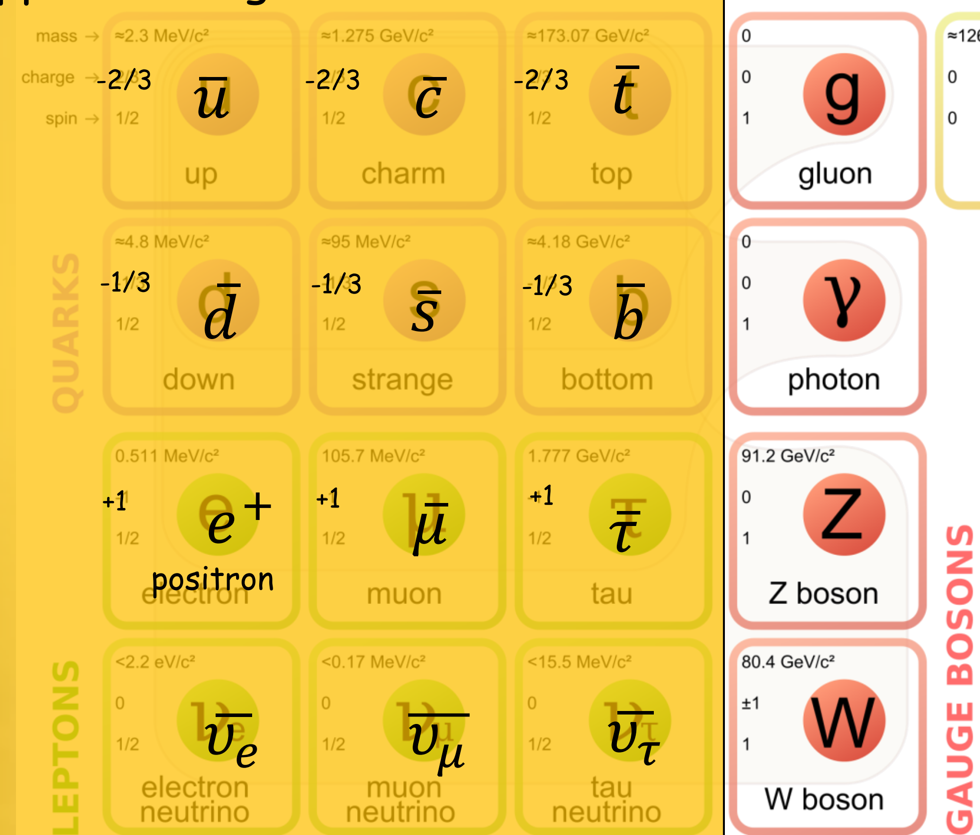
Fundamental Interactions

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

At one glance

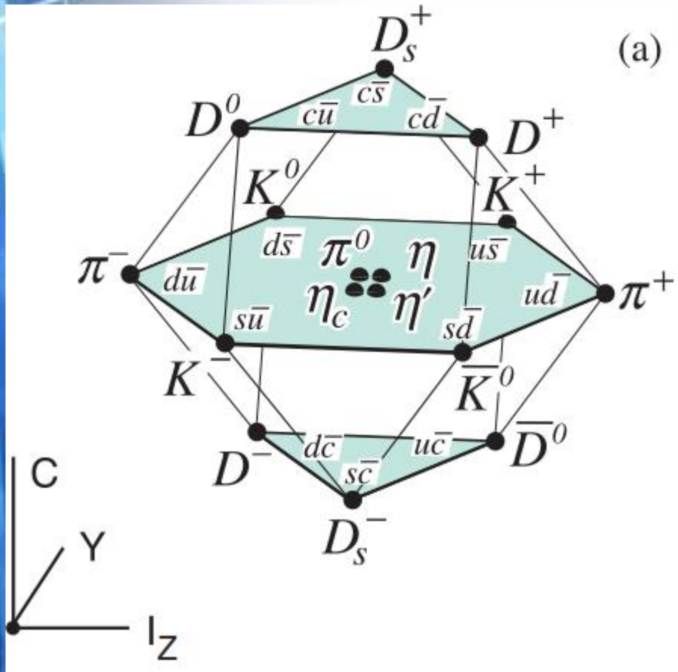
ANTIMATTER: same mass, opposit charges



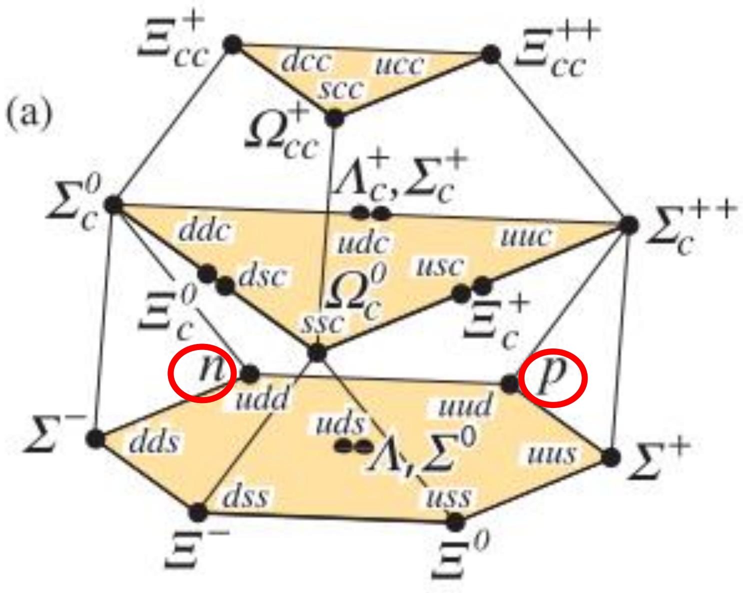
Particle classification

- Hadrons: particle sensitive to the strong interaction.
- Are hadrons:
  - Mesons, composite structures of $q\bar{q}$
  - Baryons, composite structures qqq

Quark content of some Mesons and Baryons



Multiplets of mesons ($q\bar{q}$) made of u,d, s and c quarks



Multiplets of barions made of u,d, s and c quarks

Quark-gluon plasma (QGP)

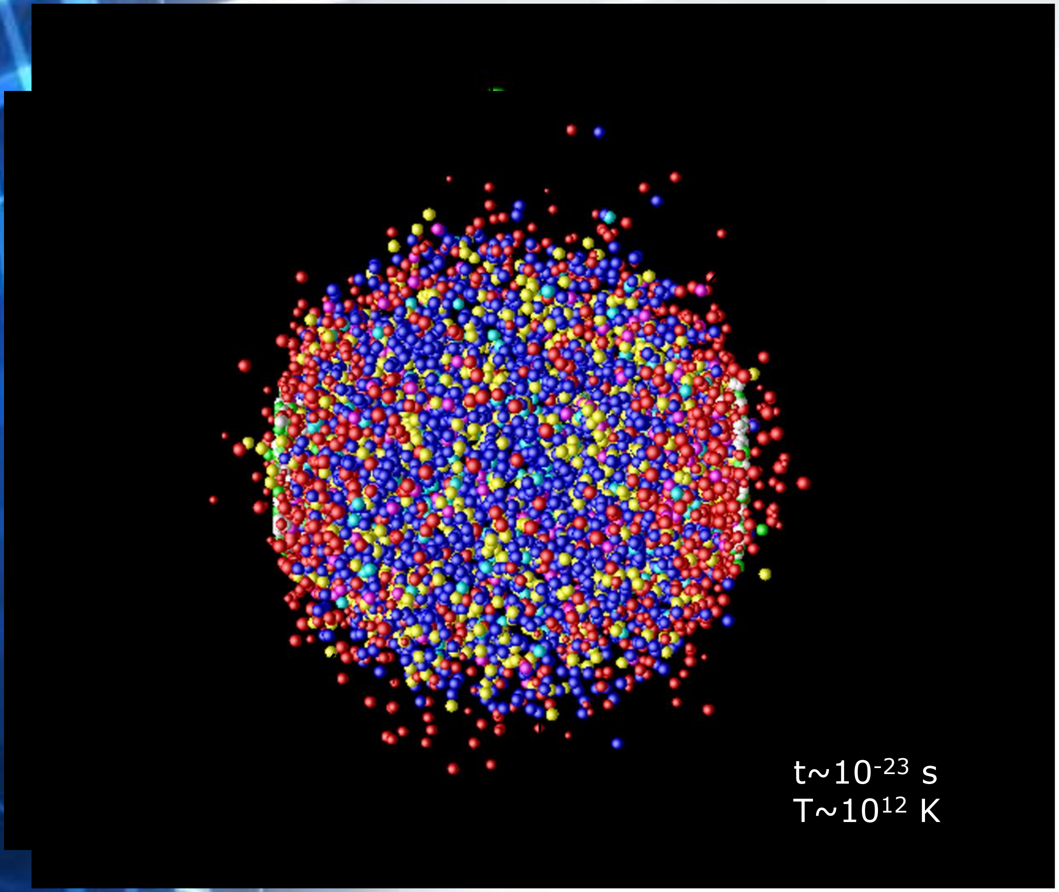
- The aim of the heavy-ion program is the study of strongly interacting matter at extreme density (~10^{14} gr/cm^3 !!) and temperature (T ~10^{12} K, considering that the sun core temperature is ~ 10^7 K!);

- This condition is supposed to exist 10^{-6} s after the big bang;

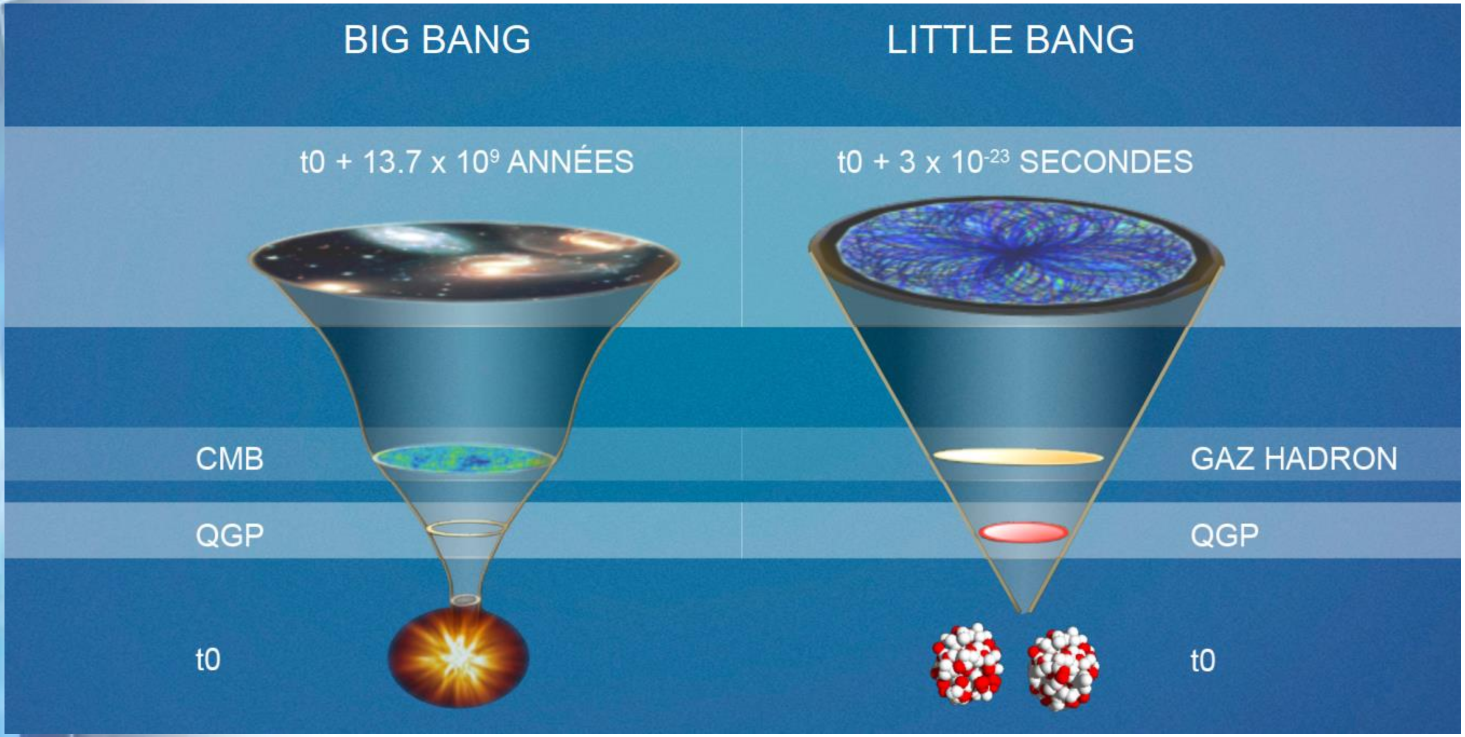
- In this conditions the quarks and gluons are not any longer confined in composite structure as protons and neutrons. They interact via the Strong Interaction.

- Some open issues to study in the QGP contest:
  - Mass problem;
  - Strangeness enhancement;
  - …….

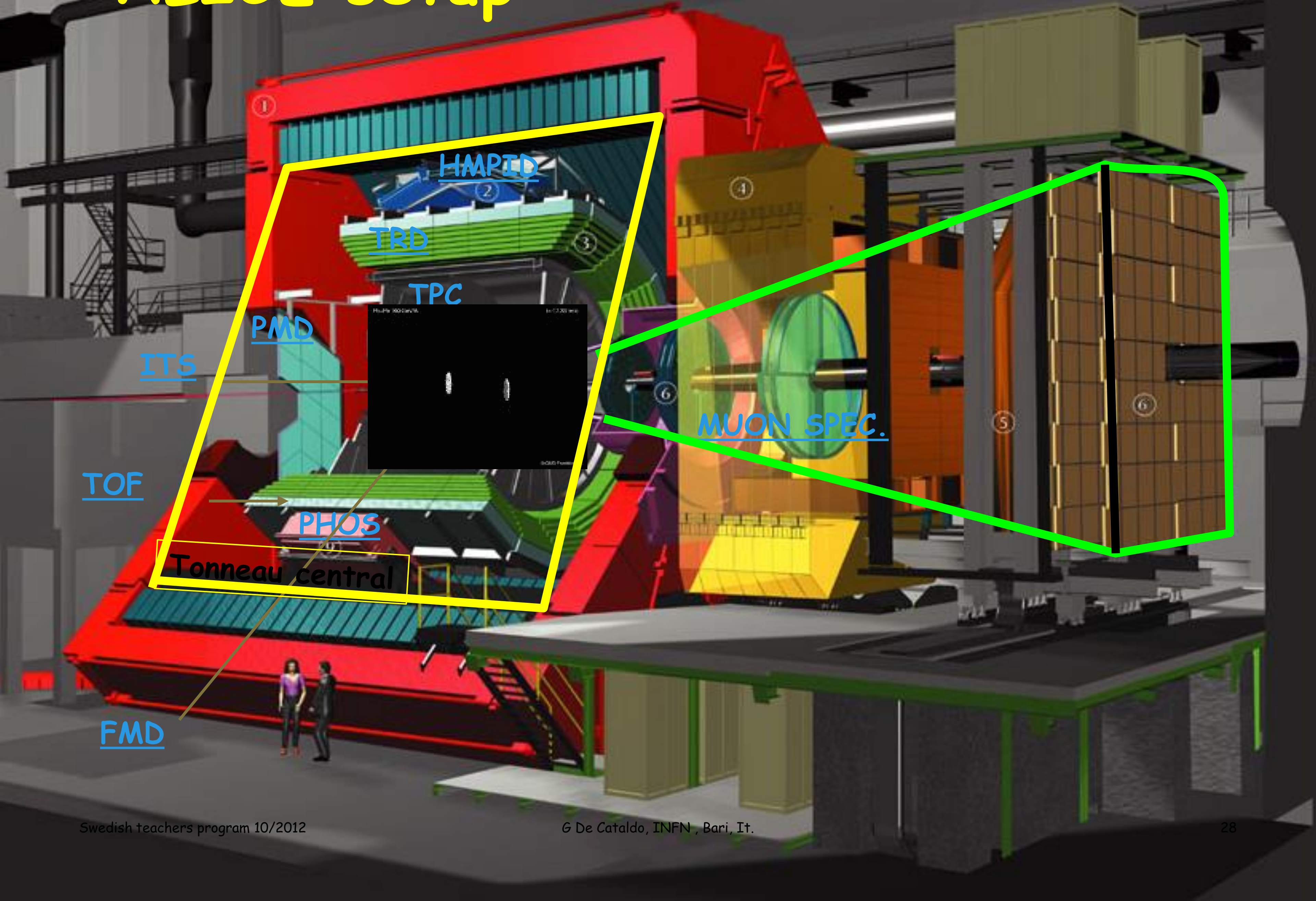
The mini big bang: let’s re-do it backward



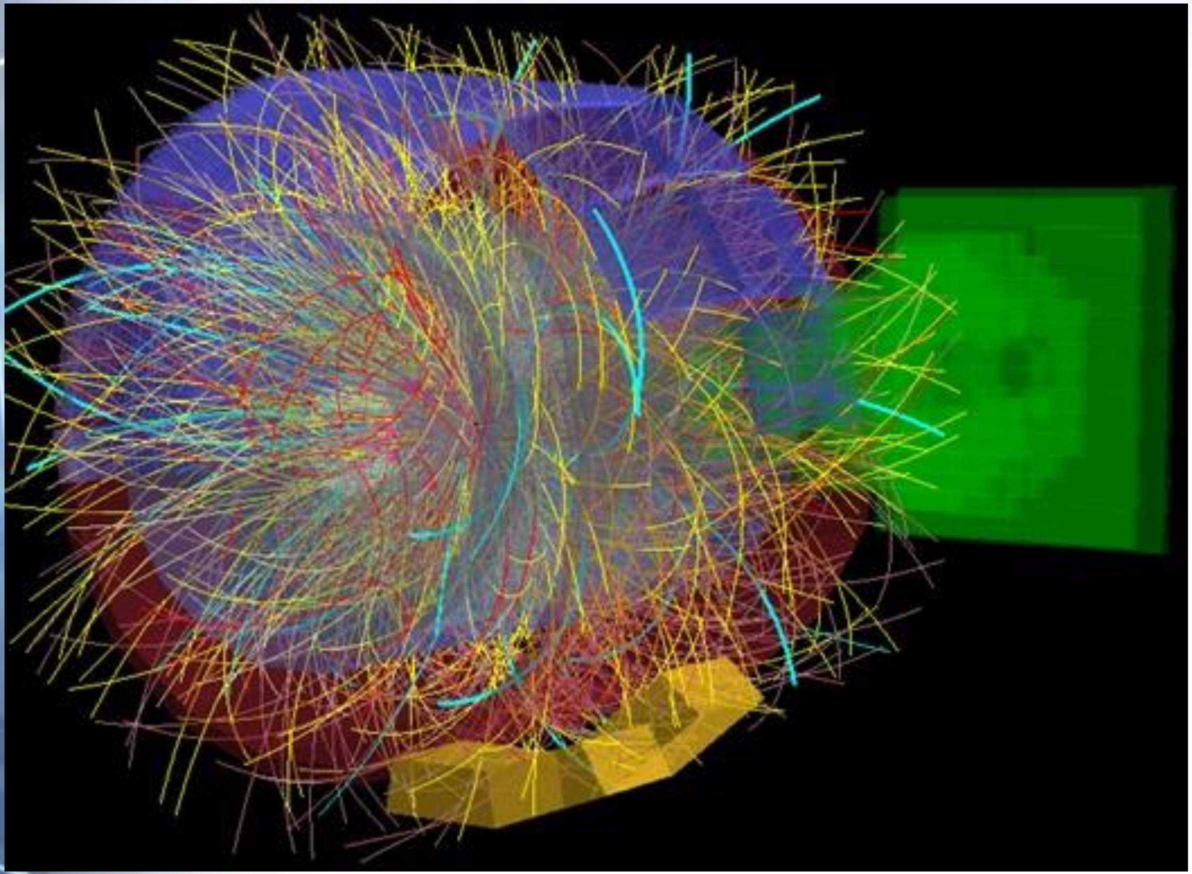
1. The accelerated lead nucleus (ordinary matter) undergo head-on collisions.
2. The collision energy materialize in quarks and gluons.
3. The de-confined quarks and gluons experience the Strong Interaction effects: this is the QGP! The soup then moves toward the equilibrium.
4. The plasma dilutes and cools down.
5. Quarks and gluons condensate to form hadrons (protons, neutrons,…): the ordinary matter!


BIG BANG
LITTLE BANG
t0 + 13.7 x 10⁹ ANNÉES
t0 + 3 x 10⁻²³ SECONDES
CMB
GAZ HADRON
QGP
QGP
t0
t0

ALICE setup

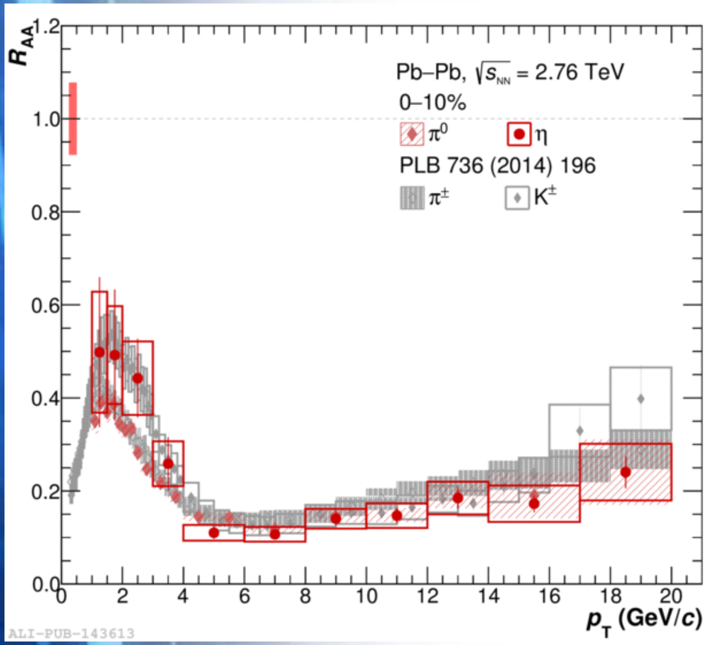


Lead Collisions 2011



The R_{AA} and QGP features

R_{AA} : The Nuclear Modification Factor



Measured nuclear modification factor for the π^0 (empty symbols) and η meson (full symbols) compared to ALICE $\pi^{\pm}$ and $K^{\pm}$ (open and full diamonds) in the centrality class 0-10%. The boxes around unity represent quadratic sum of the uncertainty on $\langle T_{AA} \rangle$ and on the pp spectrum normalization uncertainty.

QGP features

Combining several observables, ALICE concluded the QGP behaves as a "perfect liquid" , no viscosity, and not as a gas, as supposed.

Summary Lecture I

- Elementary Particles are objects showing particle-wave behavior (duality);

- Heisenberg's incertitude principle $\Delta x \Delta p \geq h$, quantization of Energy and angular momentum requires the QM and the SR for the description of the particle dynamic state. The classical mechanics inadequate;

- quarks and leptons (fermions, $\text{spin } \frac{(2n+1)}{2}\hbar \quad n = 0,1, \dots$) account for the visible mass in the Universe;

- Gauge bosons (spin=$n\hbar$ n=1,…) as interaction mediators of the three fundamental interactions:

Summary Lecture I

- the quark model simplifies the particle zoo of mesons($q\bar{q}$) and baryons (qqq) that are composite particles;
- The QGP: a perfect liquid, no viscosity, as state of the strongly interacting nuclear matter at T~10^{12} K and density ~10^{14} g/cm^3 , 10^{-6} s after the big bang.