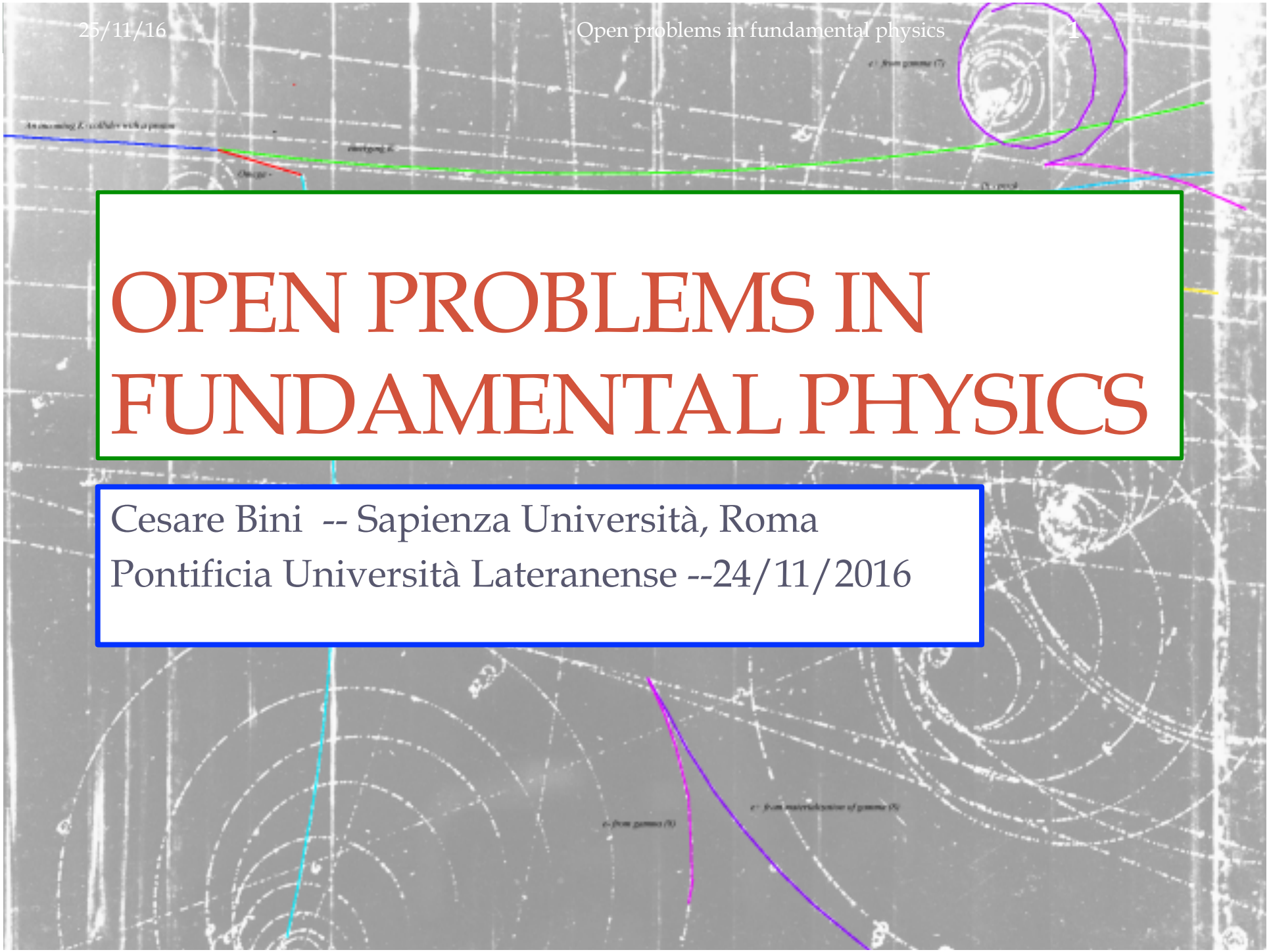

OPEN PROBLEMS IN FUNDAMENTAL PHYSICS

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Pontificia Università Lateranense --24/11/2016

Outline

- Why “fundamental physics” ?
- How such an ambitious program is carried out ?
- The elementary particle physics
  - The method
  - Where do we stand now
- Are we at the end of the story ? The open problems
- Conclusions and outlook

Why "fundamental physics" ?

- It is the answer to what most scientists actually expect: ***Nature at its deepest can be described by a limited number of fundamental laws, the description of all natural phenomenologies should at last be possible simply based on this set of laws*.**
- Characters of these fundamental laws that scientists expect:
  - **UNIVERSALITY**
  - **UNITY**
  - **SIMPLICITY, BEAUTY**

- These are expections driven by ***centuries of experience***..

Example-1: the gravitation

Any pair of particles with masses m_1 and m_2 attract each other with a mutual force given by:

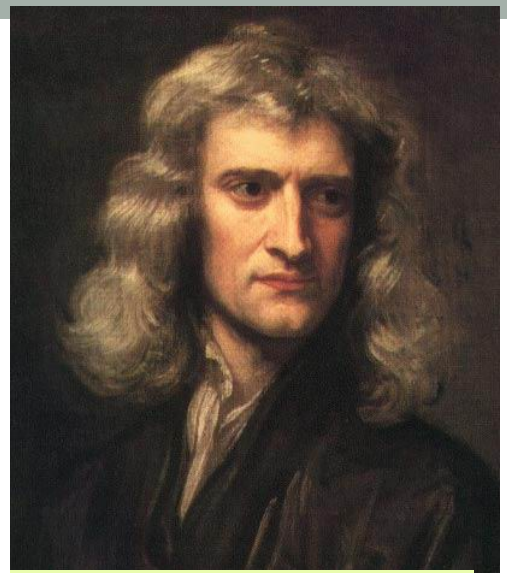
$$F = G\frac{m_1 m_2}{R^2}$$

Where:

m_1 ed m_2 = masses of the particles
R = distance between the two particles
G = "universal" constant

It is a ***UNIVERSAL law***:
"It is valid for ALL particles irrespective of how they are composed: it depends only on their masses and distance."
It gives rise to a ***UNIFICATION of different phenomena***:
"planets, stars, galaxies, our bodies on the earth surface…

In 1798 – Cavendish experiment:
Attraction btw 2 balls is measured ➔ mass of the earth !



I.Newton (1642 -1727)

H.Cavendish (1731 -1810)

Example-2: the electromagnetism

- The **Maxwell** equations:

a synthesis of

- Electricity;
- Magnetism;
- Optics.

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

J.C.Maxwell (1831 -1879)

This is ***another UNIVERSAL property of Nature:***

ρ J (charges and currents)

E B are the fields ➔ the forces

It is an ***extraordinary UNIFICATION***

Maxwell equations in relativistically covariant version: the "beauty"

$$\partial_\mu F^{\mu\nu} = -\frac{4\pi}{c} j^\nu$$

$$\partial_\mu \hat{F}^{\mu\nu} = 0$$

Maxwell understands that:
c = v (light) ~ 300,000 km/s

Here is what is the light !!!

A parenthesys: mathematics and physics

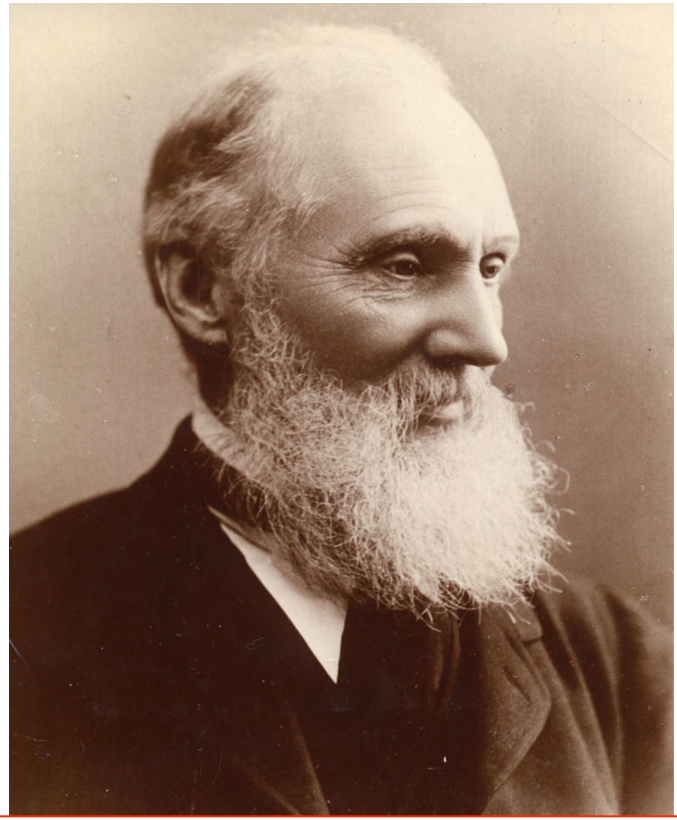
- When the properties of Nature are summarized in mathematical formulas, these reveal properties that are "hindered" by Nature itself.
- Example: the complete symmetry between E and B is not evident if we simply collect experimental facts.

- E.Wigner: "The Unreasonable Effectiveness of Mathematics" (1959)

The great illusion – around 1900…

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

Lord Kelvin: Address at the British Association for the advancement of the Science (1900)



William Thomson (lord Kelvin) (1824-1907)

But soon after 1900 completely new and unexpected phenomena were discovered and the fundamental physics re-started

How such an ambitious program is carried out ?

- Two main directions:
- **Direction1**: the ∞-ly small: ***few elementary bricks and few forces among them***. "the idea of Democritus et al." something present in most of history of philosophy.
- **Direction2**: the ∞-ly big: ***the Universe as a whole, its large scale structure, its origin, its fate***. Cosmology has been always present in any culture BUT in XXth century a cosmology based on observation has been founded !

- In the following: I go through Direction1: from *Rutherford* to *Higgs*, a whole century of discoveries…

Elementary Particle Physics: the method

Experimental side:

-- ***make things collide*** and see what comes out

-- the higher the *energy of the projectiles* and…

→the smaller the size I can resolve

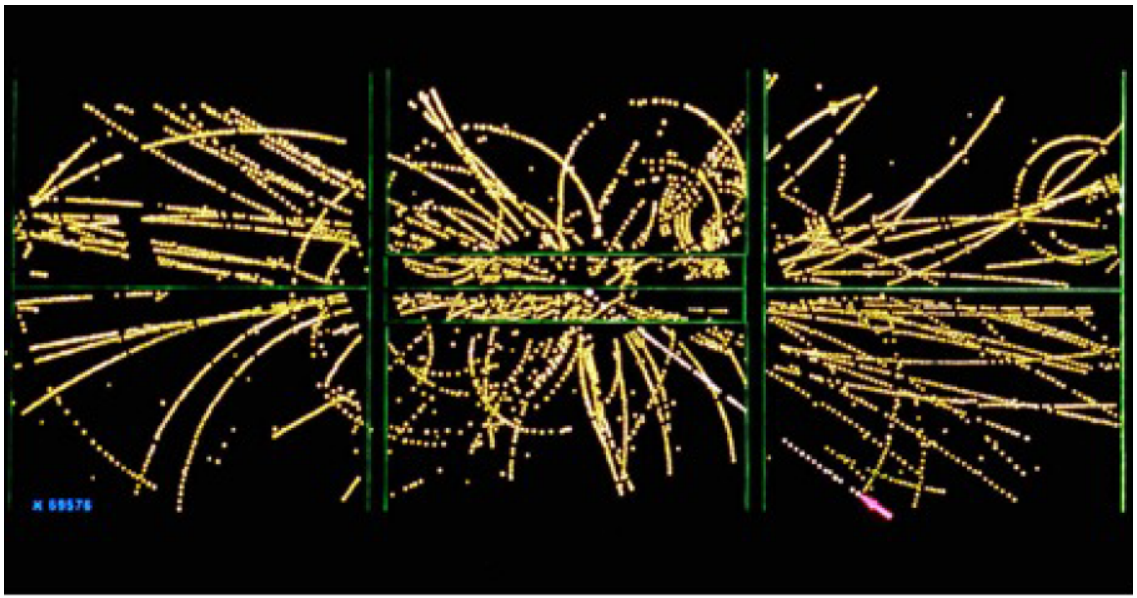
→ the larger is the number of new particles I can "***create***"

Theory side:

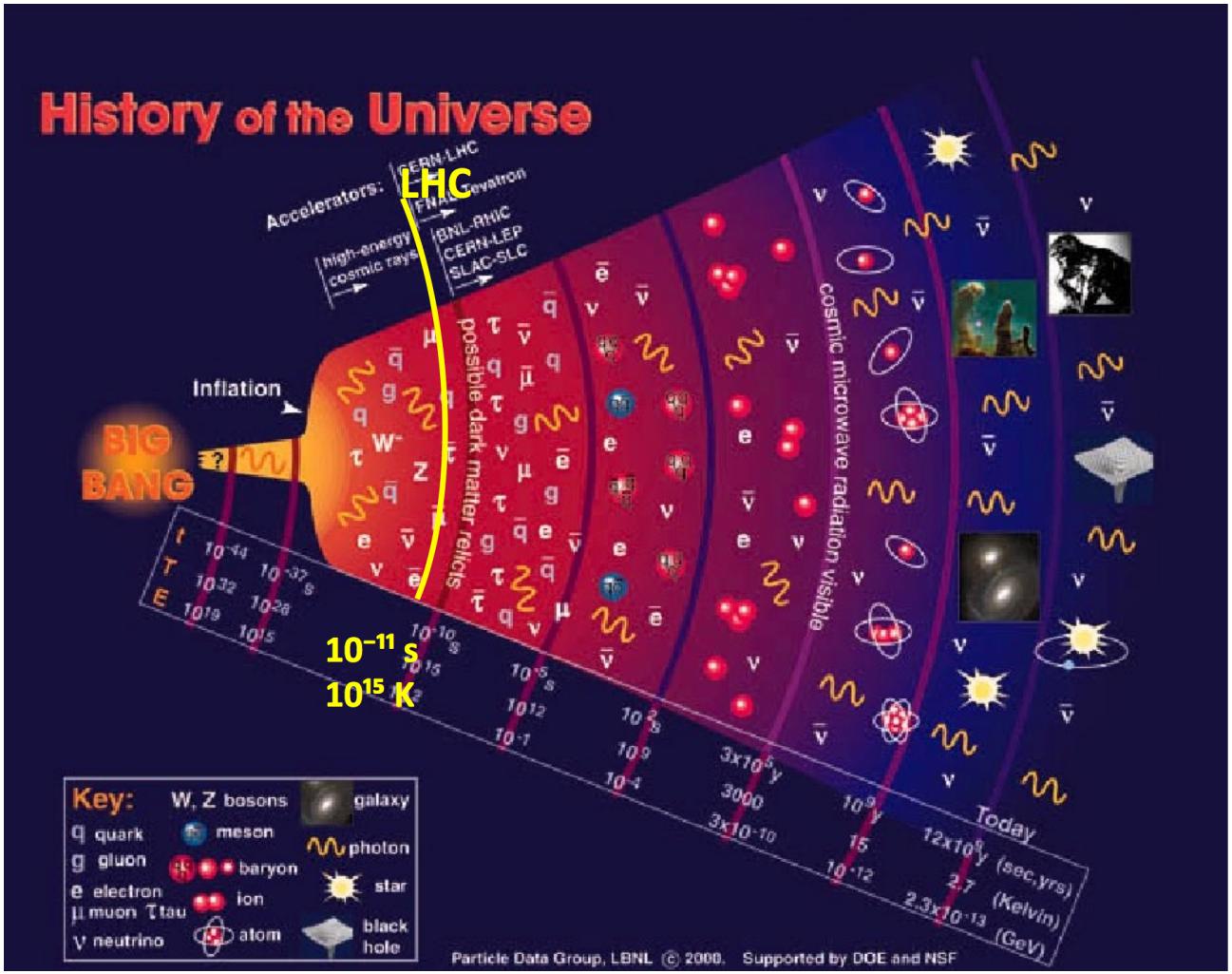
-- ***Quantum Field Theory*** is the language that puts together *quantum mechanics* and *special relativity*.

→ The **Standard Model** of elementary particles and interactions has been developed.

$$\lambda = \frac{h}{p} \approx d$$

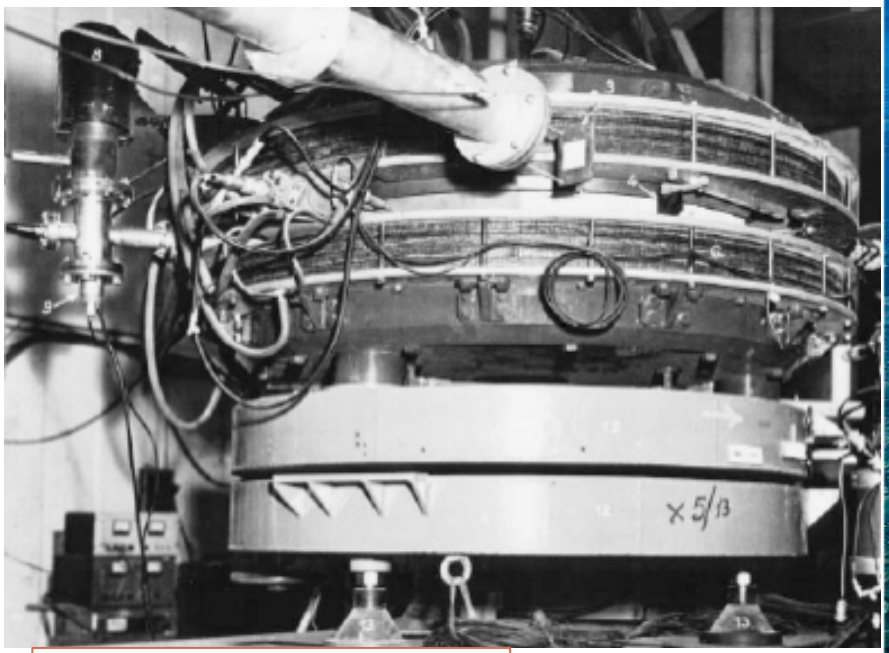


Particle – Cosmology Interplay



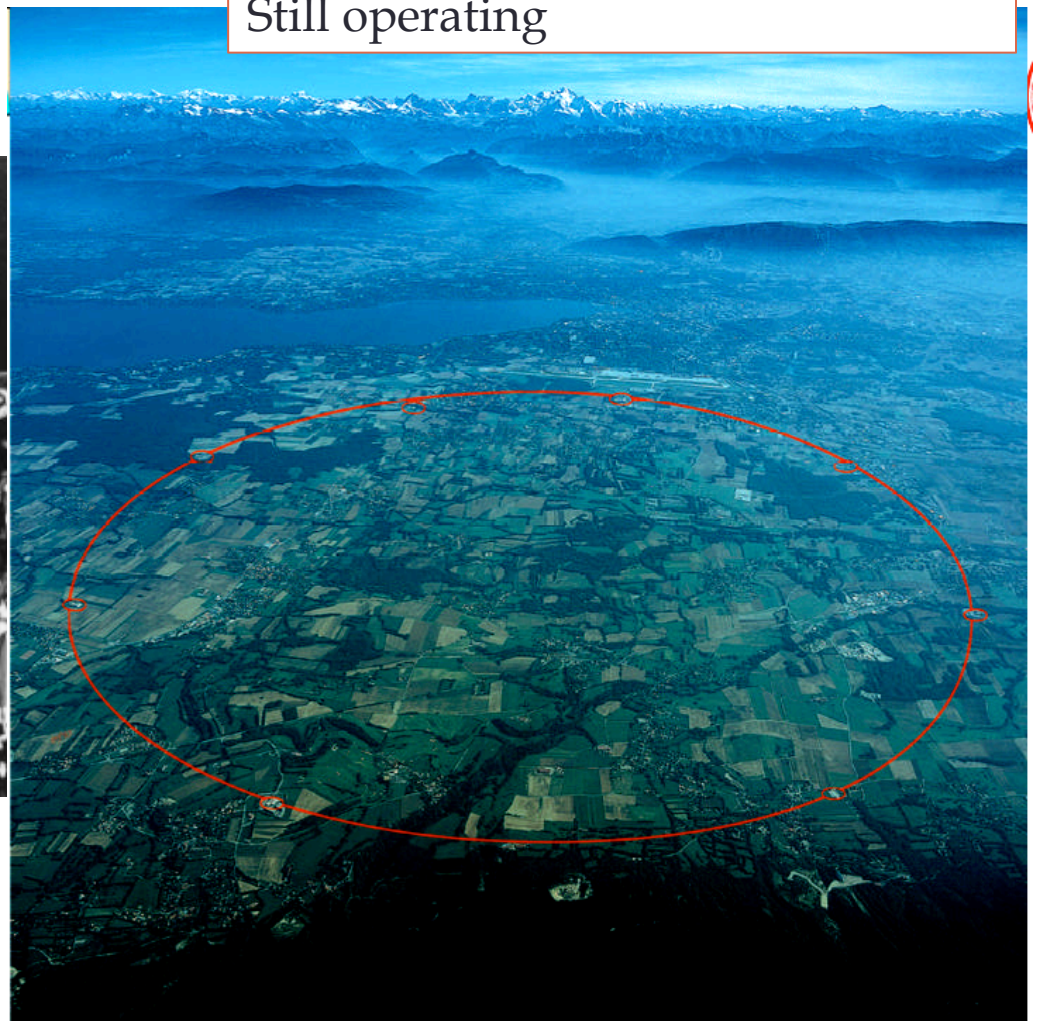
From AdA to LHC: the accelerators

Accelerators get bigger and bigger to allow particles to reach higher energies
→ To probe lower dimensions
→ To allow production of new particles



AdA: Frascati 1960's

LEP-LHC tunnel built in the 1980's
Still operating

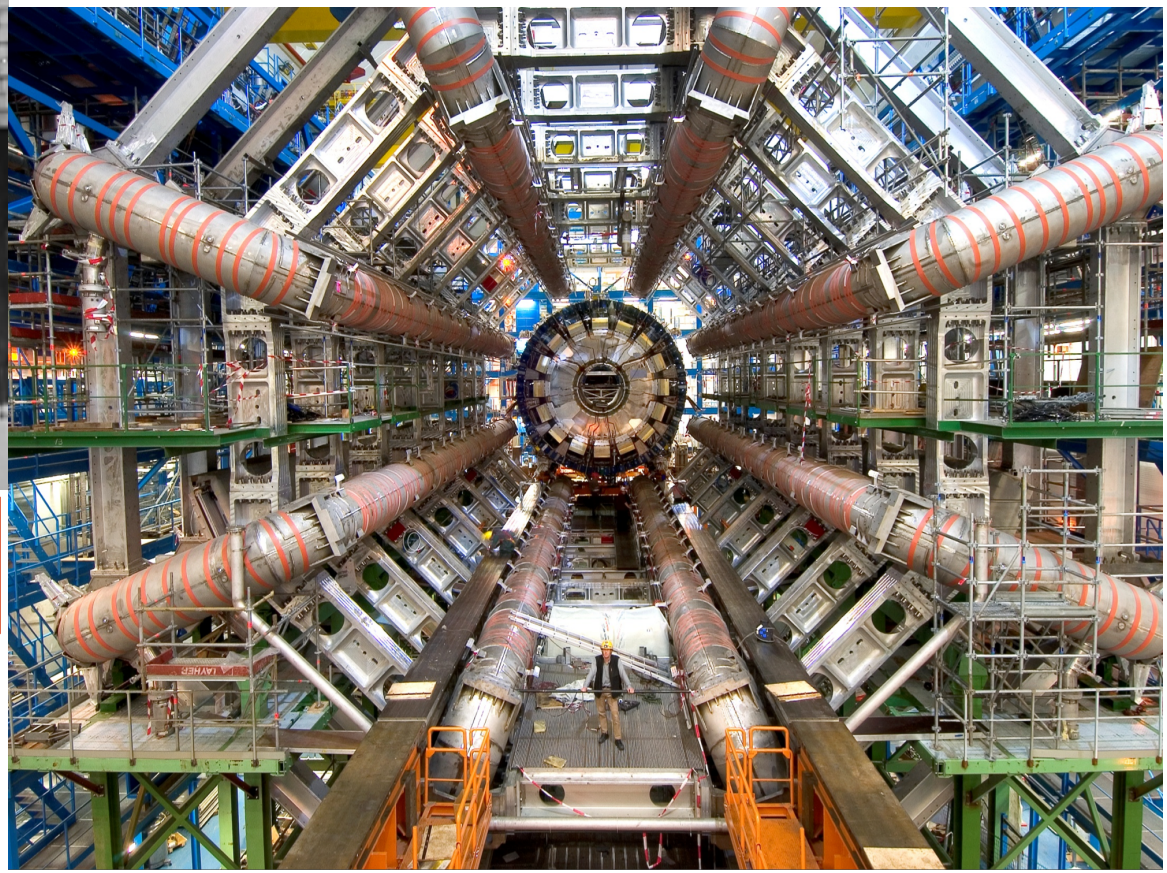


From Rutherford to ATLAS: the detectors

Detectors: the "eyes" to see the results of the particle collisions

The Rutherford experiment 1911
All the apparatus on the desk

The ATLAS experiment at LHC



The Big Science

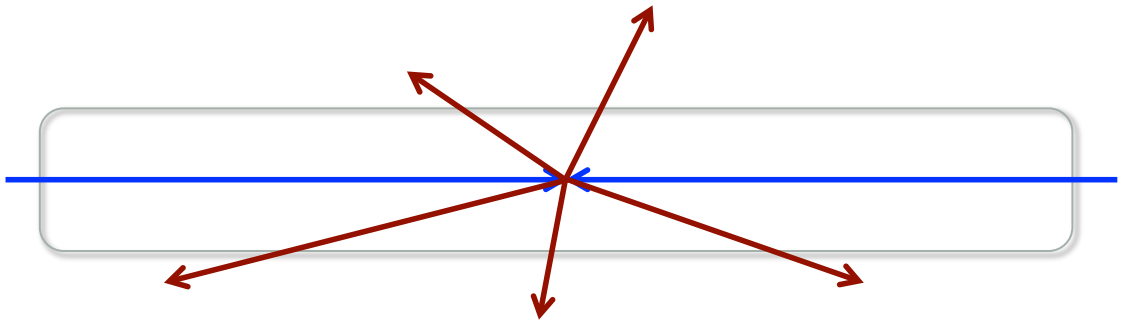
- What does it mean to do a particle physics experiment ?
  - A lot of money
  - Many people (engeneers, technicians, physicists)
  - A lot of time (from design to end of data taking, it takes 20-30 years)
- Sociological/Political implications:
  - Need of specialization
  - Management structures
  - Democracy in the choices ?
  - …

Quantum Field Theory - I

QFT: attempt to include **Special Relativity** in the framework of the **Quantum Mechanics** (started with *P.Dirac* in 1928)

➔A new mathematical language that allows to make predictions on elementary particle processes.

It is the bridge between experimental facts and our picture of fundamental structure of the Universe



For a given initial state, the probability to get a given final state

Quantity comparable with measured frequency in the experiment

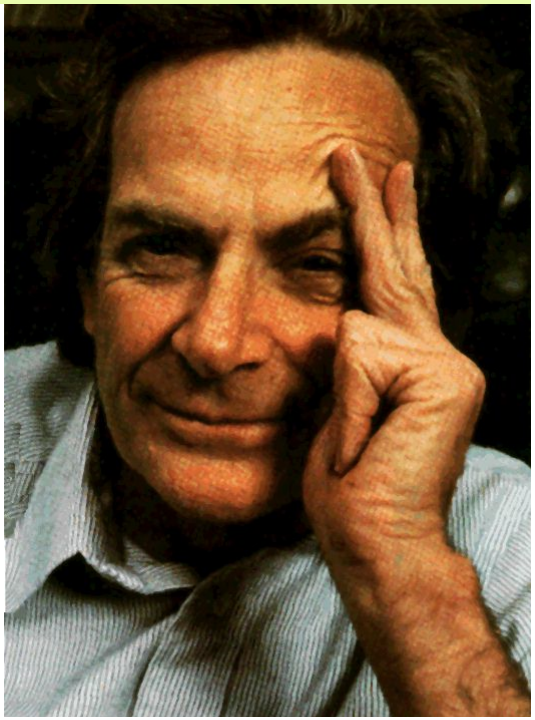
The **FIELD** is the fundamental entity, what is a **FIELD** ?

Quantum Field Theory - II

What is a FIELD ? It is a complex function of space-time f(x,t). Quantized oscillations can be excited and give rise to particles.

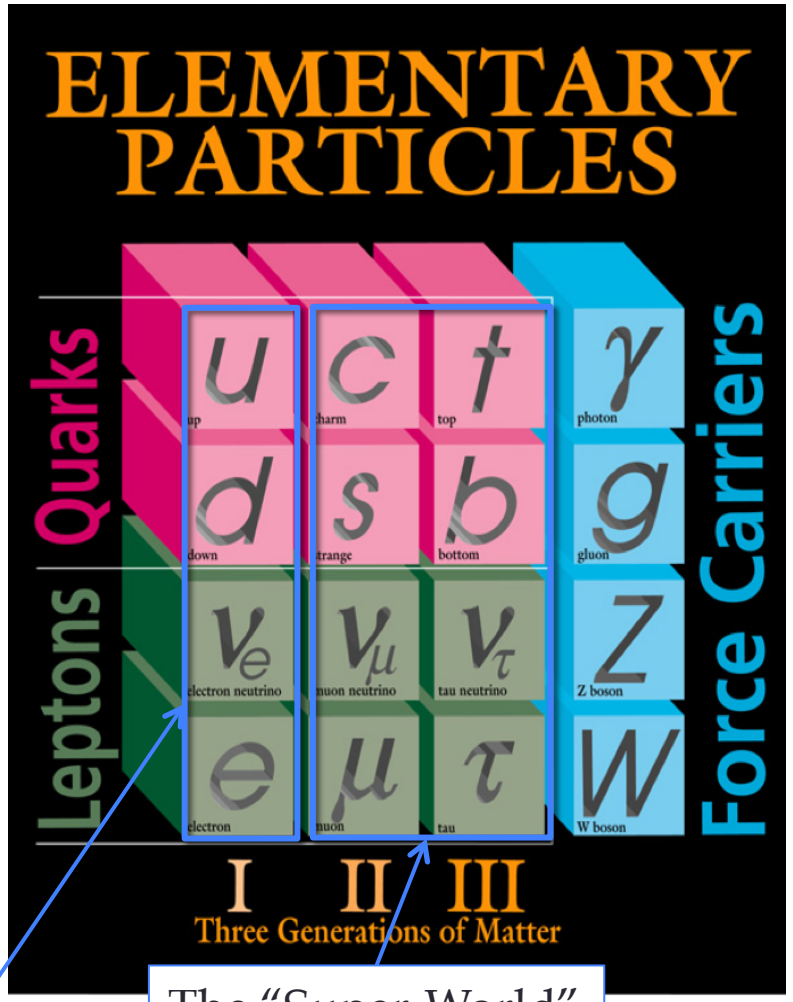
Elementary particles *are described as fields.*
But also ***forces*** *are described as fields !!*
A new approach to what a "force" is:
→ Interactions through the exchange of "mediators" fields ("gauge bosons" γ, W/Z, g)

R.P.Feynman (1918 -1988)



The elementary fields: the new "periodic table"

- What is really elementary in the Universe ?
- Elementary particles (the bricks):
  - **Quarks** (6 types)
  - **Leptons** (6 types)
- Force Mediators:
  - **Photon** (electromagnetism)
  - **W/Z** (weak nuclear)
  - **Gluon** (strong nuclear)
- The gravitation is missing



Ordinary matter atoms,…

The "Super-World"

Where do we stand now ?

- The **Standard Model** (many authors, Dirac, Schwinger, Feynman, Glashow, Weinberg, Salam, t'Hooft, Higgs,…)
- A description of the elementary particles and their interactions in terms of fields ➔ predictions of quantities that can be measured. It is a "*testable*", "*falsifiable*" theory

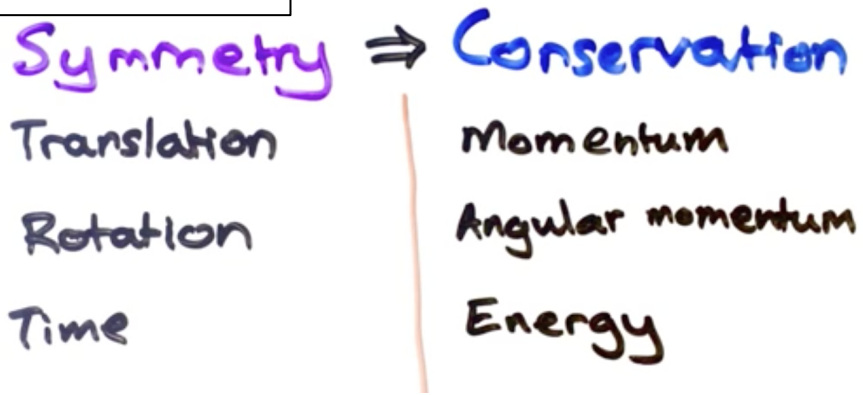
The Standar Model Lagrangian

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)}\\
& +(\bar{\nu}_L, \bar{e}_L)\bar{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) && \text{(lepton dynamical term)}\\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] && \text{(electron, muon, tauon mass term)}\\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right] && \text{(neutrino mass term)}\\
& +(\bar{u}_L, \bar{d}_L)\bar{\sigma}^\mu iD_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) && \text{(quark dynamical term)}\\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] && \text{(down, strange, bottom mass term)}\\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right] && \text{(up, charmed, top mass term)}\\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$

The "heart" of the Standard Model

- How is the Standard Model Lagrangian built ??
- The driving line of this building was the respect of **symmetry properties** (*Lorentz* and *gauge* symmetries).

Noether's theorem



- The form of the interactions is somehow a consequence of the request of symmetry:

"*Symmetry dictates the interaction*"

Crisis and a solution

- Crisis (in the '60s): *the mass terms* violate the symmetry properties, but we observe the masses. How is this possible ?
- ➔ Idea of P.Higgs, R.Brout and F.Englert: a new field directly interacting with all other fields give them the property to have a rest mass. ***This allows to maintain the symmetry properties of the theory***
- How an idea can be accepted ?

Only if it makes predictions that can be tested

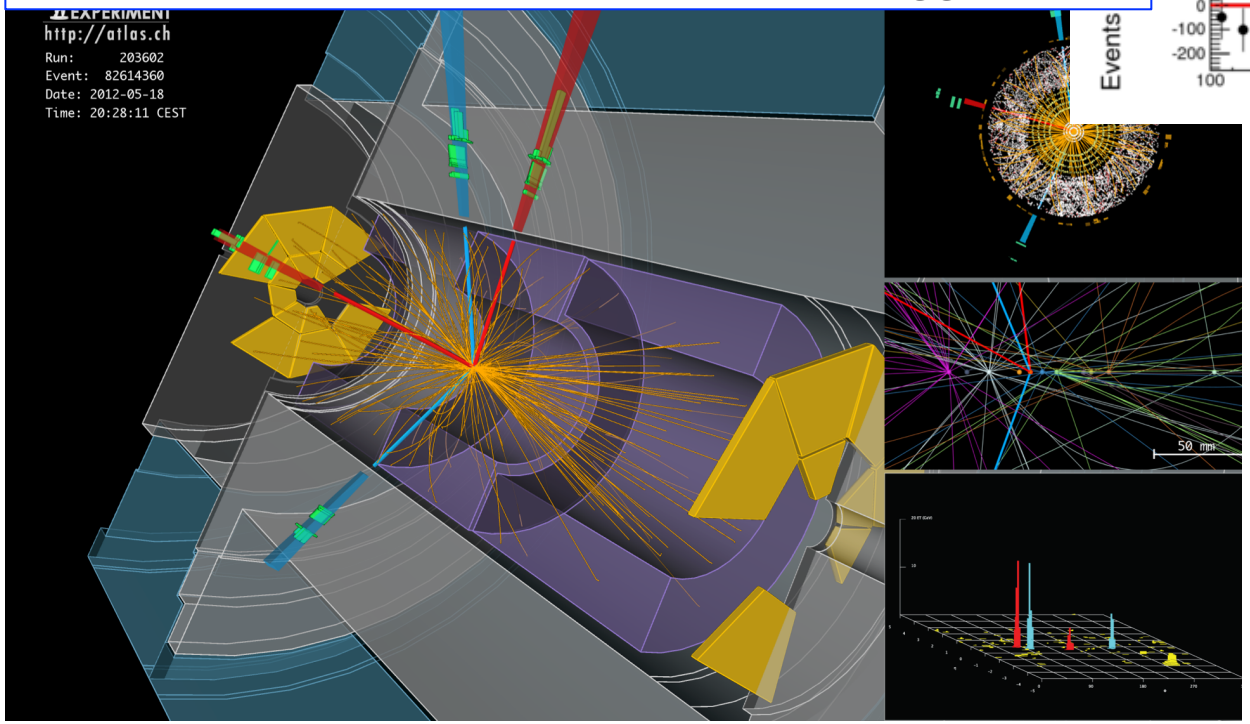
The predictions is: **the Higgs field give rise to a particle with specific decay properties:**

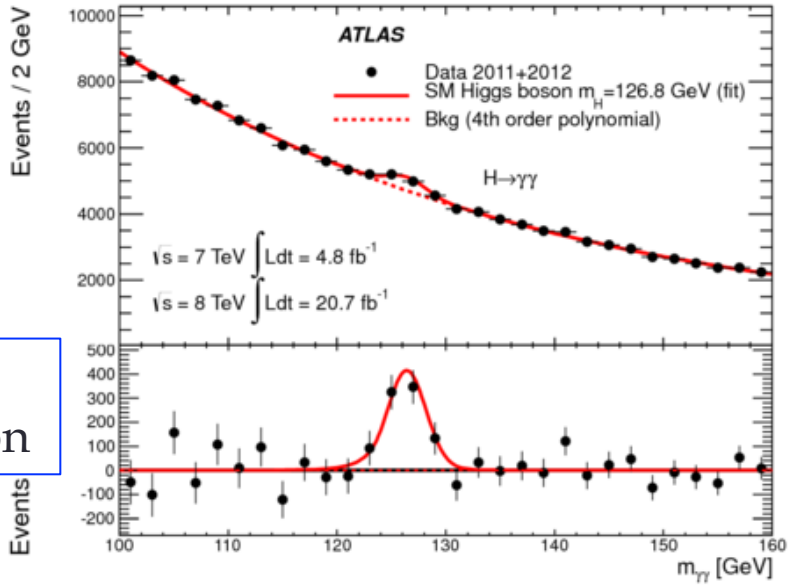
➔ Experiments to look for this particle

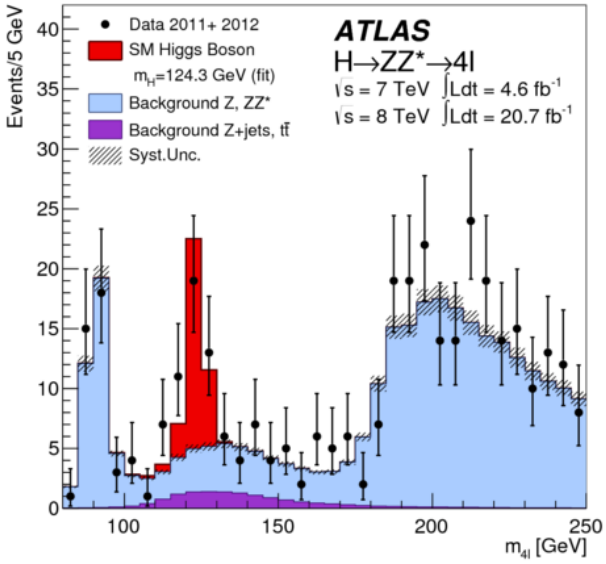
Higgs hunting: 1964 – 2012…

How an idea can be accepted ?
Only if it makes predictions that can be tested
The predictions is: the Higgs field give rise to a particle with specific decay properties:
➔ Experiments to look for this particle

2012: ATLAS and CMS @ LHC
Observes a particle consistent with the Higgs boson

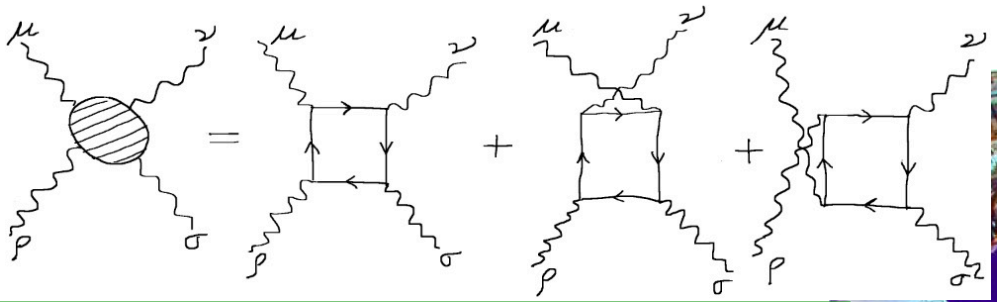






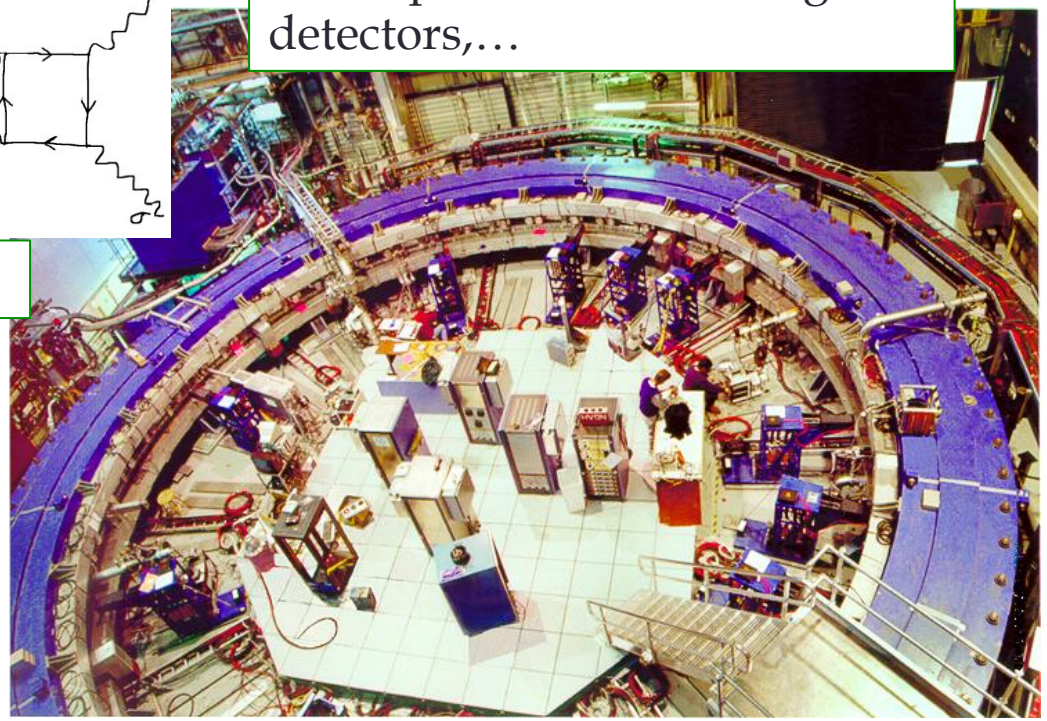
Is the Standard Model in good health ?

- Definitely YES ! All predictions done are in agreement with available experimental results.
- An example: the magnetic moment of the muon



The theory: many, many calculations…

The experiment: iron, magnets, detectors,…



Experiment : = $(116591802 \pm 49) \times 10^{-11}$

Theory : = $(116592089 \pm 63) \times 10^{-11}$

So: are we at the end of the story ? Is the Standard Model the "Theory of Everything" ?

- Can we, in 2016 say what Lord Kelvin said in 1900 ?
- NO: there are two categories of problems:

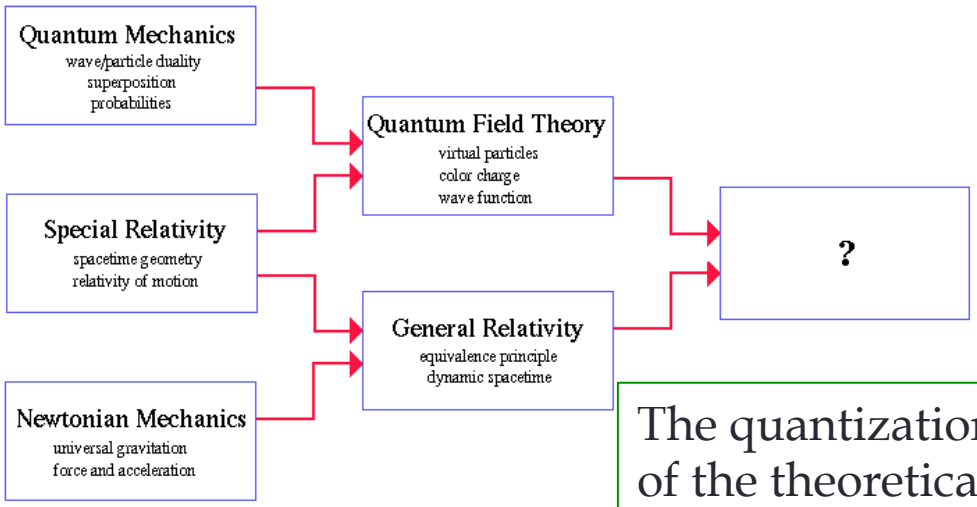
The SM is ***incomplete***

The SM is ***logically unsatisfactory***

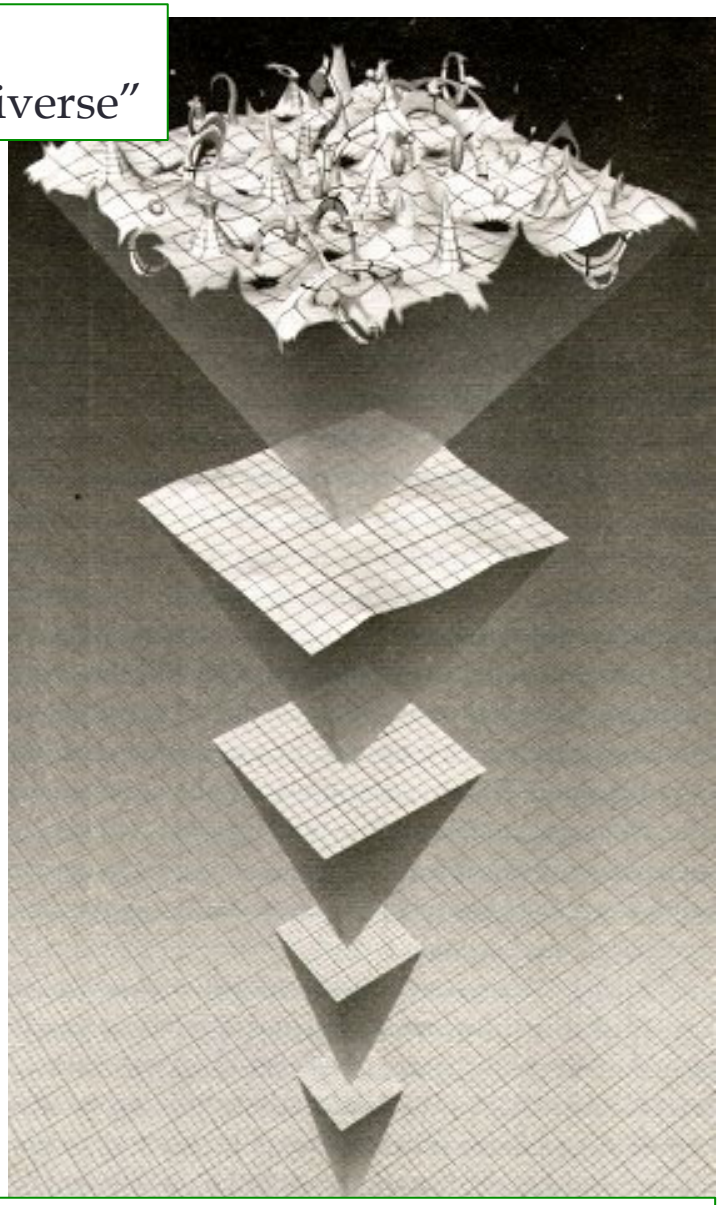
- In the following, a list of 6 "Open problems"

1) What about gravitation ?

- The Standard Model doesn't include gravitational processes.
- Gravitation is described by the General Relativity, a "classical" theory.
- Quantum effects are "incompatible" with the smooth space-time of general relativity.



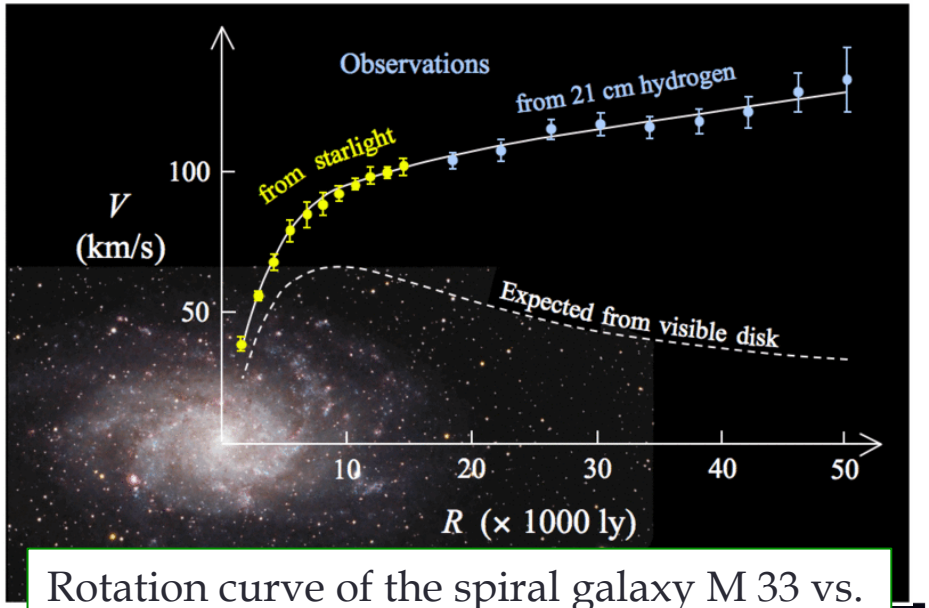
From B.Greene
"The Elegant Universe"



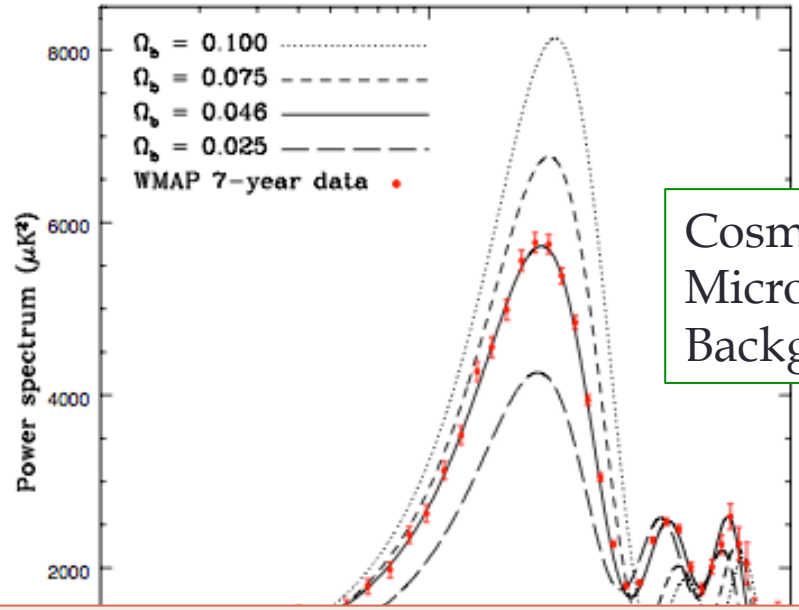
The quantization of the gravitational field is a "dream" of the theoretical physics since several decades…

2) The dark matter

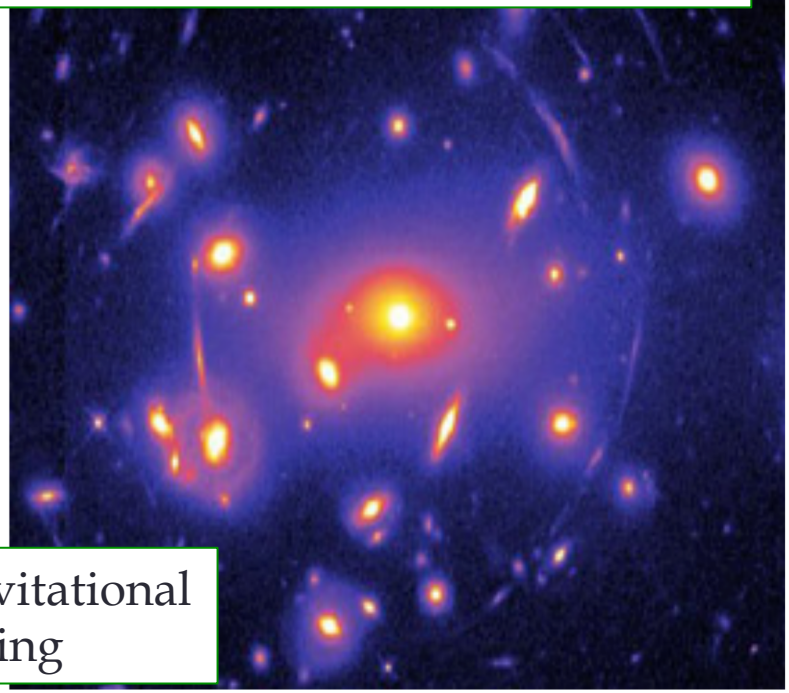
Several indications of existence of Dark Matter (85% of the total)
→ From astronomical observations
→ From cosmological data



Rotation curve of the spiral galaxy M 33 vs. predictions based on visible matter only



Cosmic Microwave Background

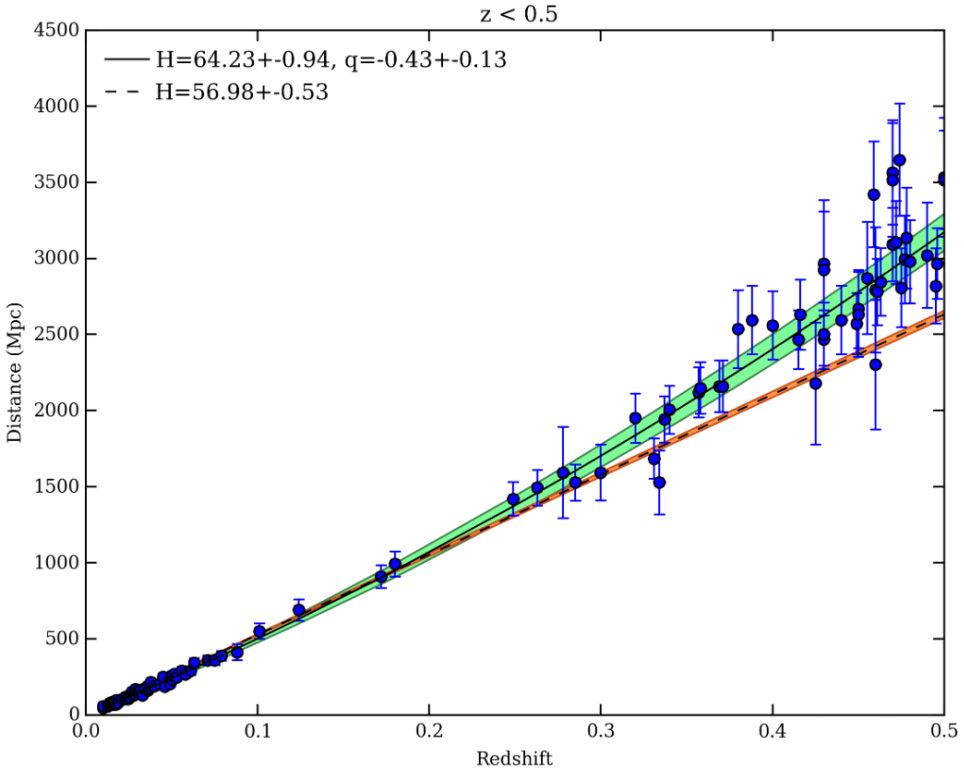


Gravitational lensing

The search for the Dark Matter is open since long time (LHC, Gran Sasso Lab.,…) but still nothing solid found…

3) The dark energy

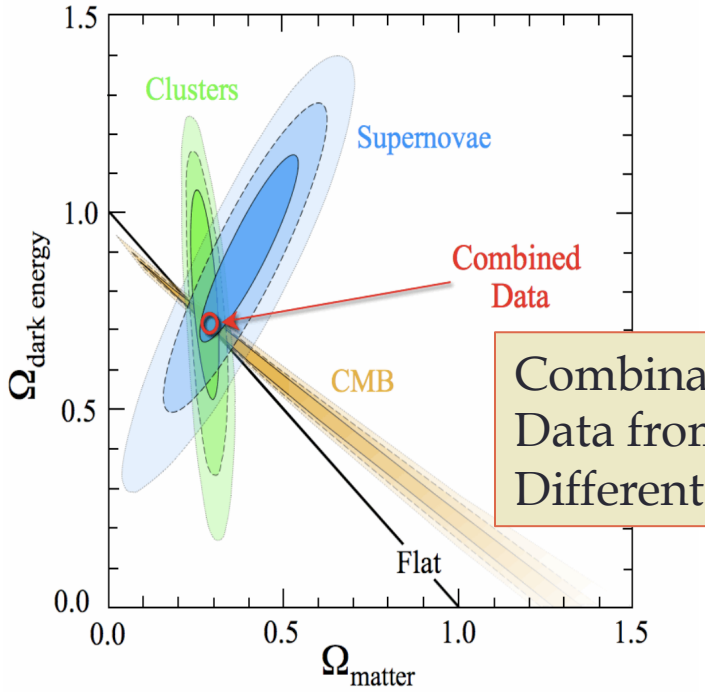
Observation (in the '90s) of the ***accelerating universe expansion***
➔There must be a "repulsive driving force" against gravitation
➔The picture is compatible with a **"cosmological constant" Λ**, an energy permeating the Entire Universe.



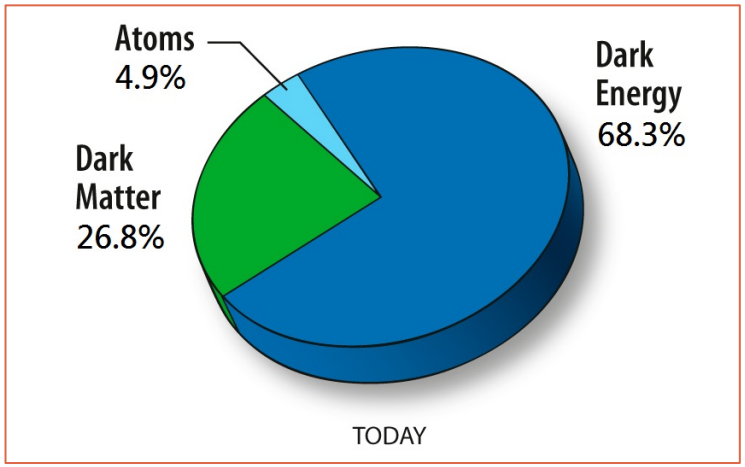
The value of **Λ** is out of our understanding. What is it ? It is apparently the most significant ingredient of our Universe. And we don't know it at all…

The emerging picture: the Dark Universe

The Universe is "flat" and "Dark-Energy" dominated.
The Standard Model accounts only for less than 5% of the full energy budget of the Universe.



Combination of Data from several Different sources



Only 5% of the total energy of the Universe is accounted by the Standard Model…

Many direct and indirect searches are ongoing on both Darks

4) The matter-antimatter asymmetry

- **Anti-Matter**: postulated by P.Dirac in 1928 soon discovered (positron) in 1932, almost "symmetric" with matter. **BUT**:
  - **Why is our Universe done with Matter only ??**
- **Baryogenesis** problem: in order to explain the present matter-antimatter asymmetry $\eta = (n_B - n_{AntiB})/n_B \approx 10^{-9}$ we need some symmetry "violations":
  - **Violation of baryon number conservation**
  - **C and CP-violation**
- The Standard Model accounts for both but not with in a sufficient way.
- ➔ **No solution for the baryogenesis problem.**

5) Too many parameters

About ***20 parameters*** in the SM:

-- masses of the elementary particles

-- intensities of the interactions

Numbers not predicted, to be measured.

This is not acceptable.

Why these values ?

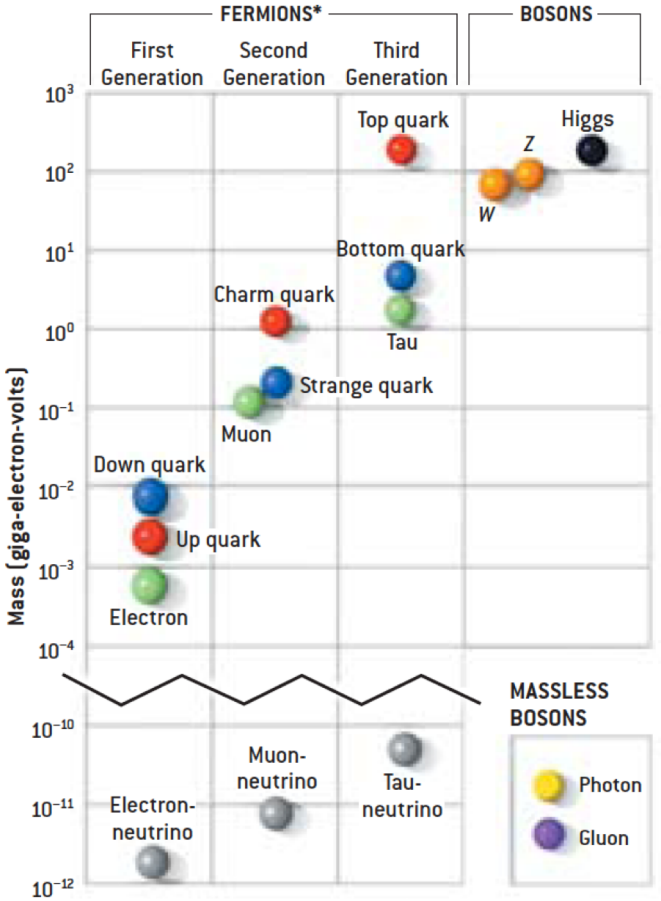
Is any theory able to predict them ?

Moreover: why the four fundamental forces have so different intensities ?

From this argument:

→ **Anthropic principle**

→ **Multiverse conjecture…**



Force	Intensity	Range (m)
Gravity	10^{-35}	∞
Nuclear weak	10^{-15}	10^{-15}
Electromagnetic	10^{-2}	∞
Nuclear strong	1	10^{-18}

6) Something unnatural…

There is something very unsatisfactory for theorists…

➔ The Higgs mass:

The experiment finds $m_H = 125$ GeV

The theorist calculates it:

$$m_H = m_{bare} + m_{corr}$$

m_{bare} is a "free parameter", $m_{corr} = 10^{18}$ GeV !!

→ the theorist has to assume mbare = $125 - 10^{18}$ GeV

➔ The Cosmological Constant:

From observation we find $\Lambda = (10^{-3}\ \text{eV})^4$

The theorist calculates it:

$$\Lambda = \Lambda_{bare} + \Lambda_{corr}$$

Where $\Lambda_{corr} = (10^{12}\ \text{eV})^4$

→ the theorist has to assume $\Lambda_{bare} = (10^{-3} - 10^{12}\ \text{eV})^4$

In both cases a "fine-tuning" is needed, very unnatural to believe

A solution please…

- Many attempts in the market.
  - GUT (Grand Unified Theories)
  - SuperSymmetry
  - Hidden Valley
  - String and Super-String theories
  - Extra-dimensions
  - …
- Any new fundamental theory should provide predictions that can be tested in experiments
- The Program:
  - ENERGY frontier
  - INTENSITY frontier
  - SENSITIVITY frontier

CONCLUSION

The Fundamental Physics has been and is a wonderful adventure of many people with several still OPEN problems to solve.

The Standard Model is from many points of view "unsatisfactory"

The impression is that the "end of the story" is far from being reached: any step forward opens new frontiers to face like a "bottomless pit"