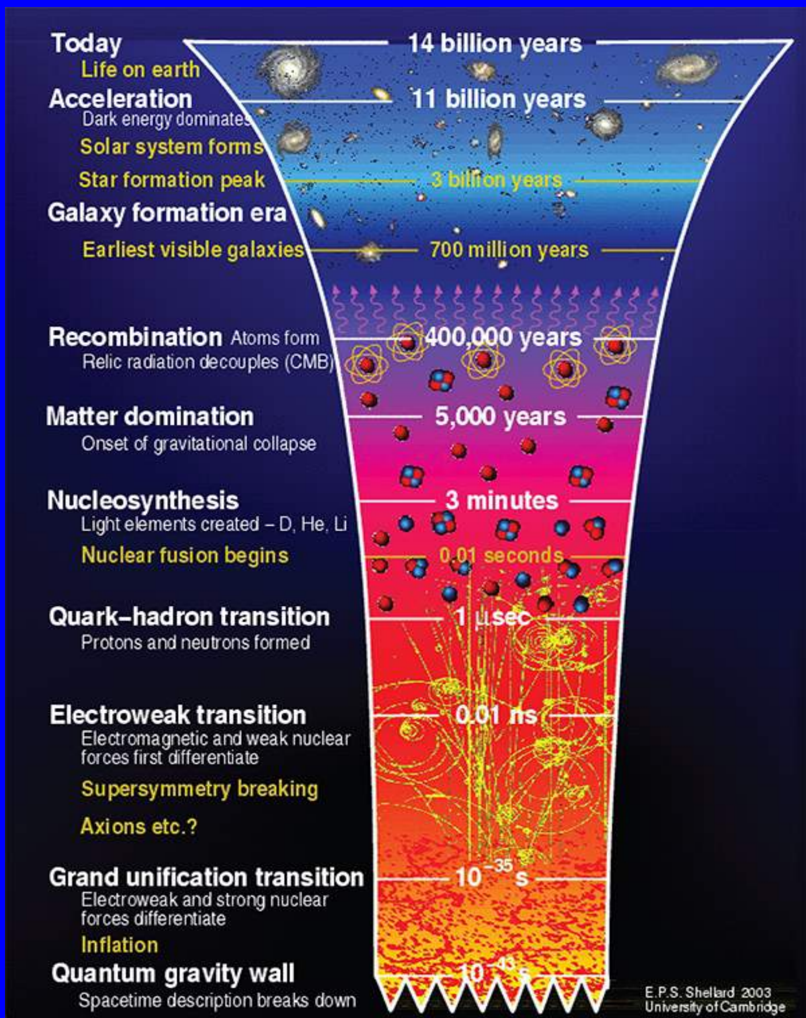
# The Higgs boson and its (plausible) history: from LHC to the early Universe


Germano Nardini,

DESY - University of Bern

# The (extrapolated) history of the Universe

## Some characteristics:



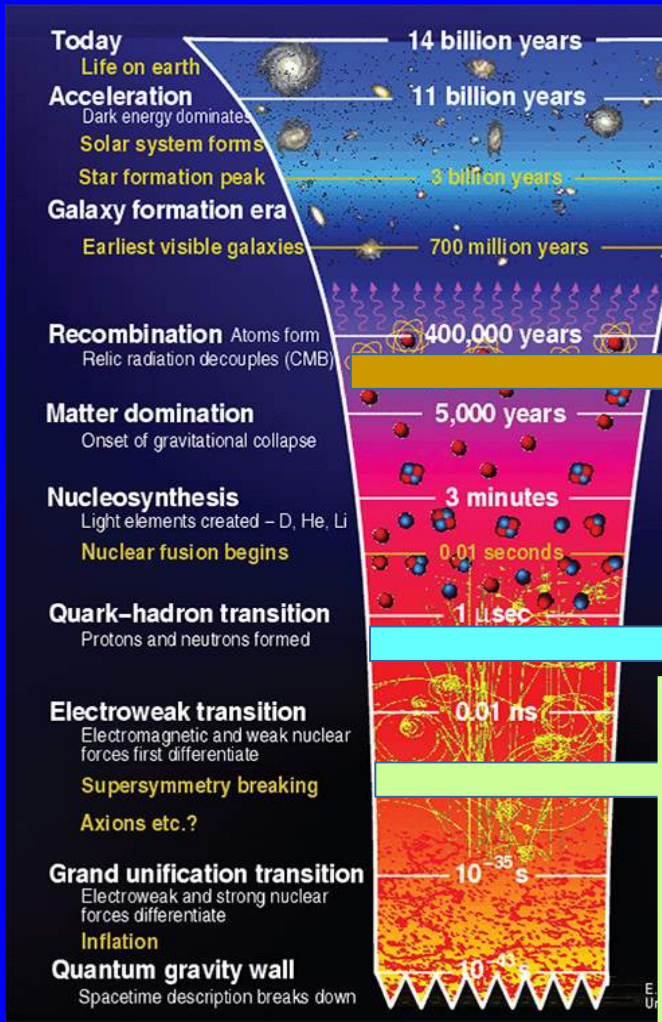

| Temp.[K] | Density [gr/cm$^3$] | Energy [GeV] | Size |
|---|---|---|---|
| 1 | $10^{-30}$ | $10^{-12}$ | 1 |
| $10^3$ | $10^{-21}$ (>atom) | $10^{-9}$ | $10^{-3}$ |
| $10^{10}$ | 10 (>water) | $10^{-3}$ | $10^{-9}$ |
| $10^{15}$ | $10^{28}$ | $10^3$ | $10^{-15}$ |

# The (extrapolated) history of the Universe

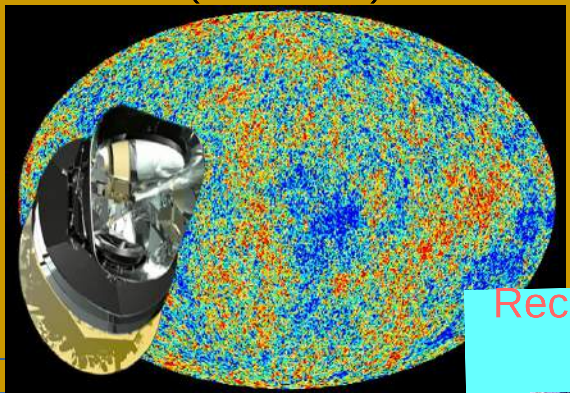
The borders of our knowledge

Energy [GeV] Size

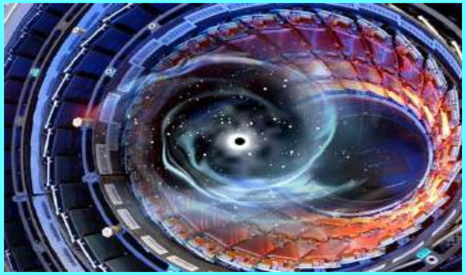
$10^{-12}$ 1




Looking at the visible universe (PLANCK)

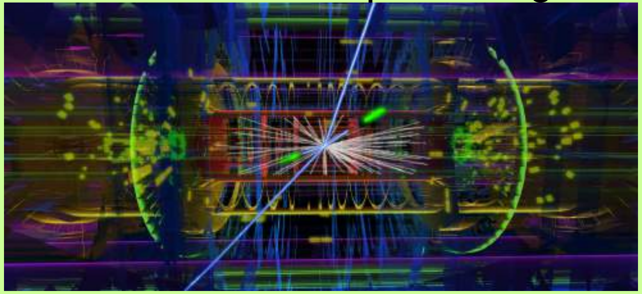


Reconstructing the universe (RHIC , ALICE)



$10^{10}$ 10 (>wa

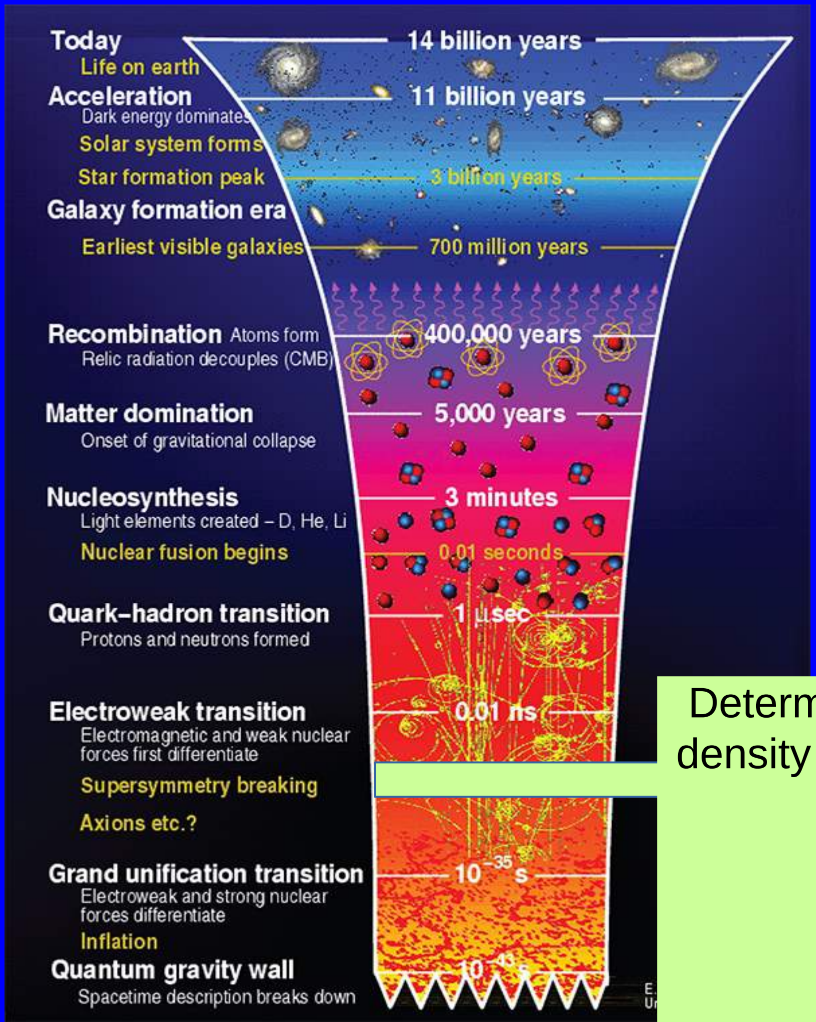
Determining the particle content without reproducing the density (ATLAS, CMS)



# Our plan ...

First: The particle content of the Universe and the newcomer (facts)

Second: The role of the new guest when the Universe was very hot and extremely young (inferring and maybe true)

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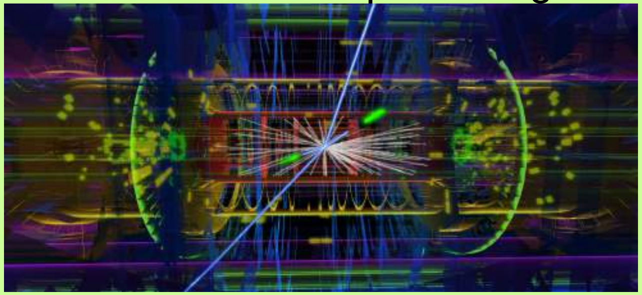


# FACTS


FaKtS


WINNER OF BEST ANIMATED SHORT FILM
2004 ACADEMY AWARDS
Harvie Krumpet
Some are born great,
some achieve greatness,
some have greatness
thrust upon them
....and then there
are others.

# Brief history of elementary particle discoveries

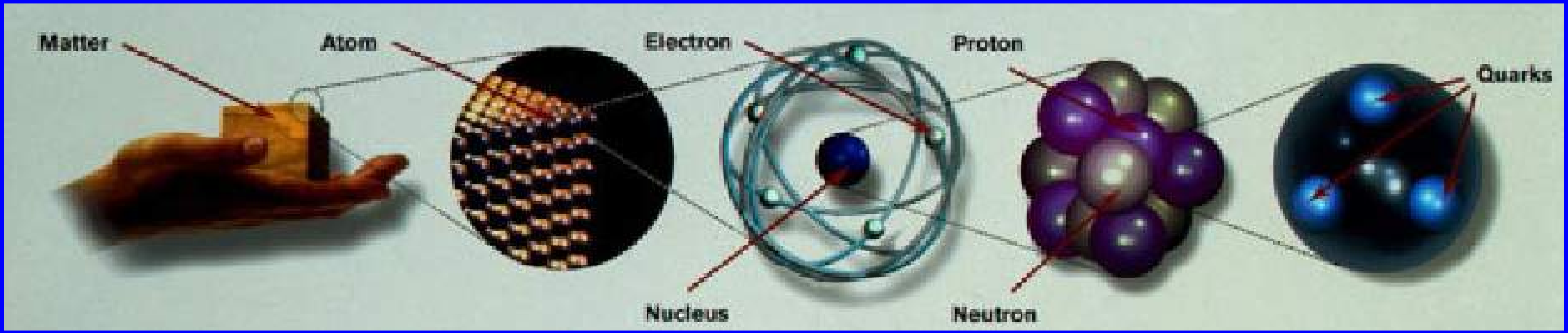
"Elementary" is a concept quite old and evolving ...


Democritus
460 – 370 B.C.

- There are various basic elements from which all matter is made
- Everything is composed of small atoms moving in a void
- Some atoms are round, pointy, oily, have hooks, etc. to account for their properties
- Ideas rejected by leading philosophers because void = no existence

# Brief history of elementary particle discoveries

"Elementary" is a concept quite old and evolving ...



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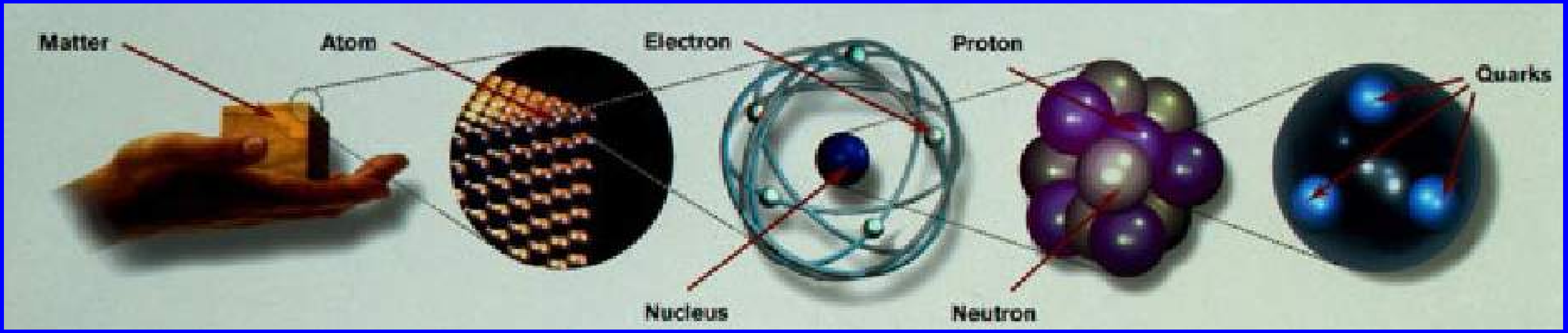
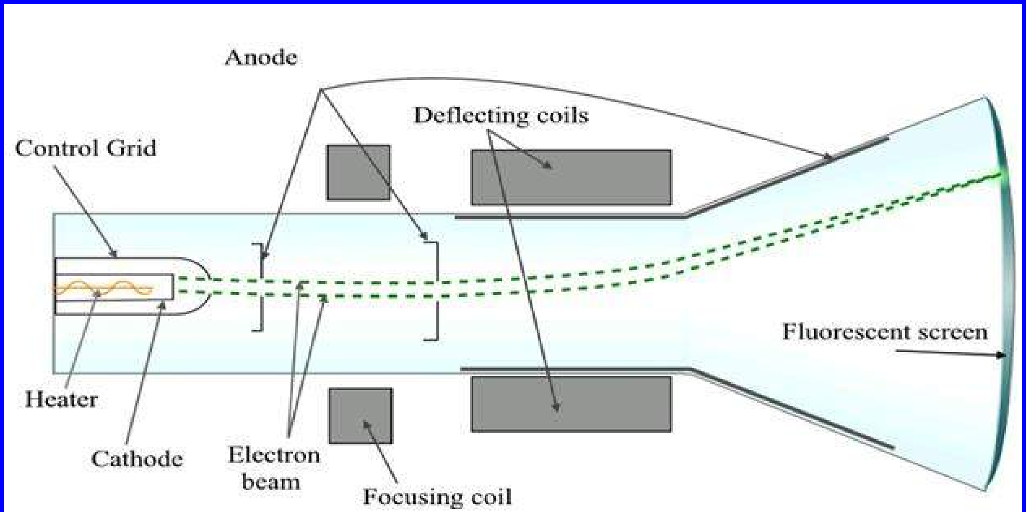



… but the first elementary (??) particle that has been discovered is the electron (1896).

# Brief history of elementary particle discoveries

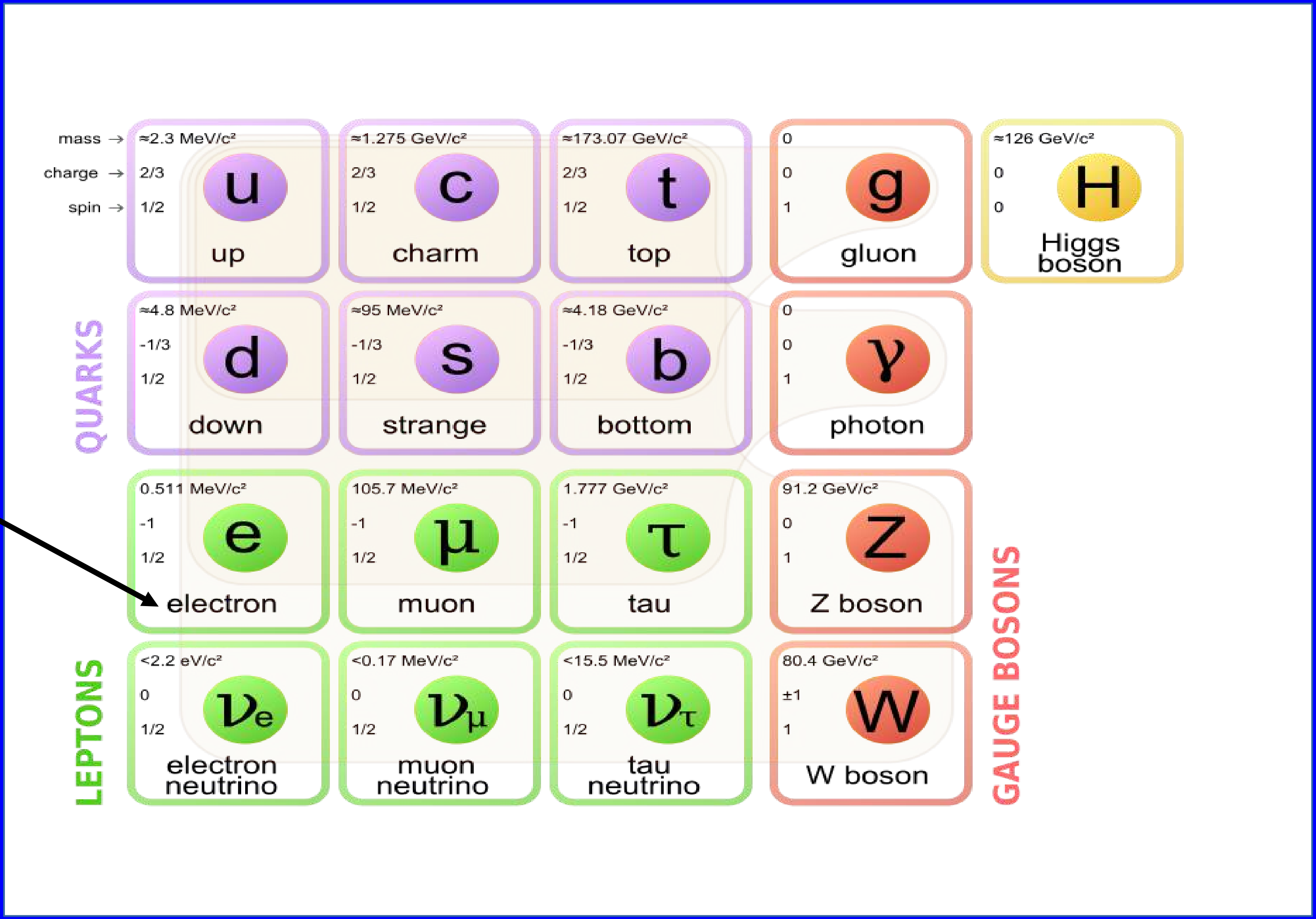
Thomson built the first particle accelerator...




Sir J.J. Thomson 1856-1940

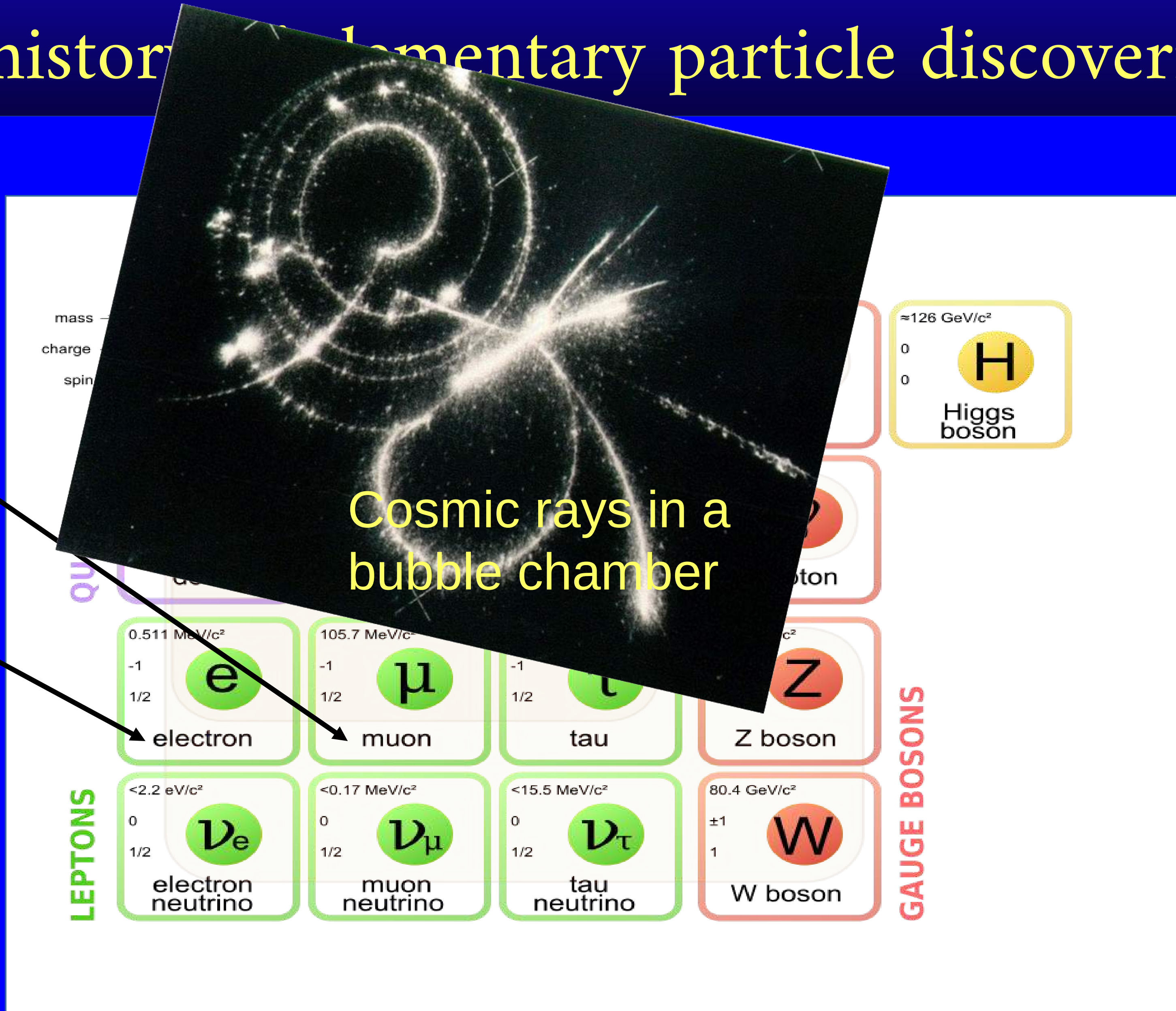
...and proved that there exists a particle with a given charge and mass (actually, he measured their ratio. Millikan disentangled the two quantities)

# Brief history of elementary particle discoveries




1896

# Brief histor … lementary particle discoveries



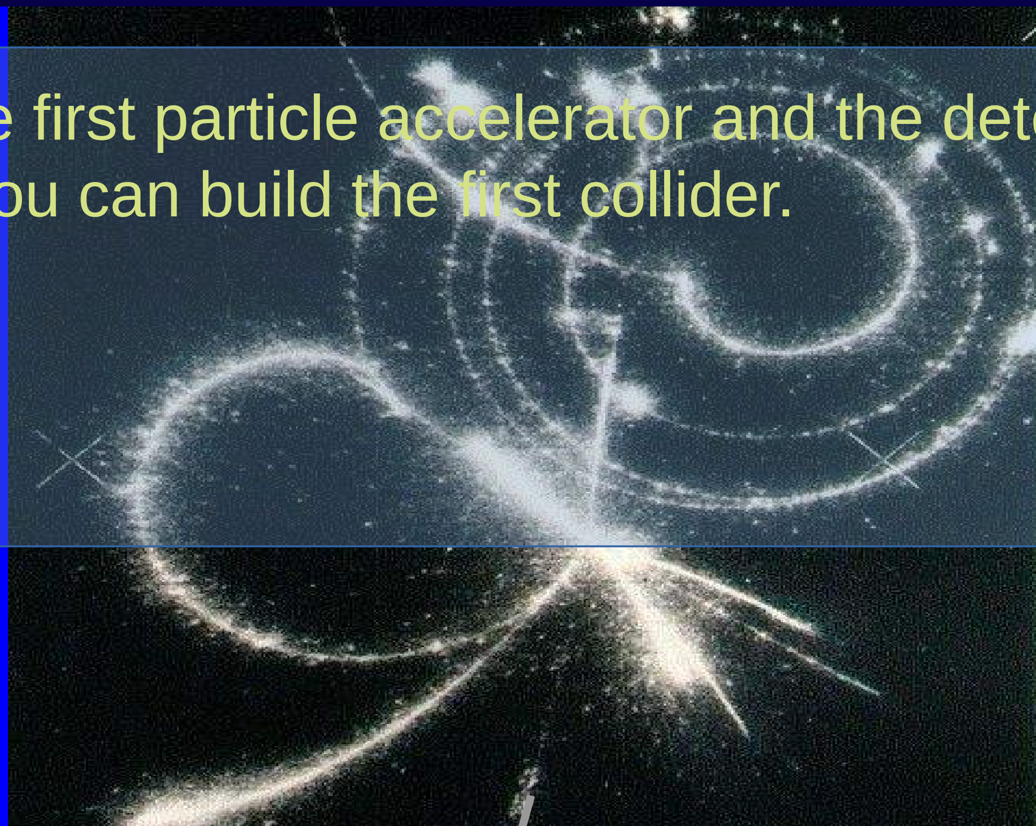

1936

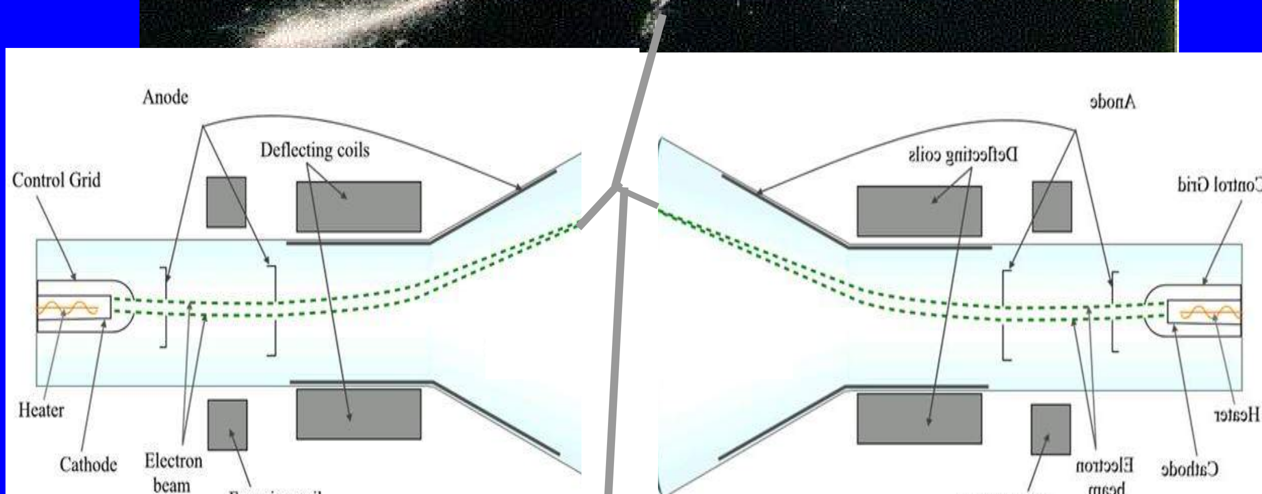
1896

Bubble chambers are "phase transition" detectors. The superheated gas liquefies where charge particles pass. The particle path is a bubble track.

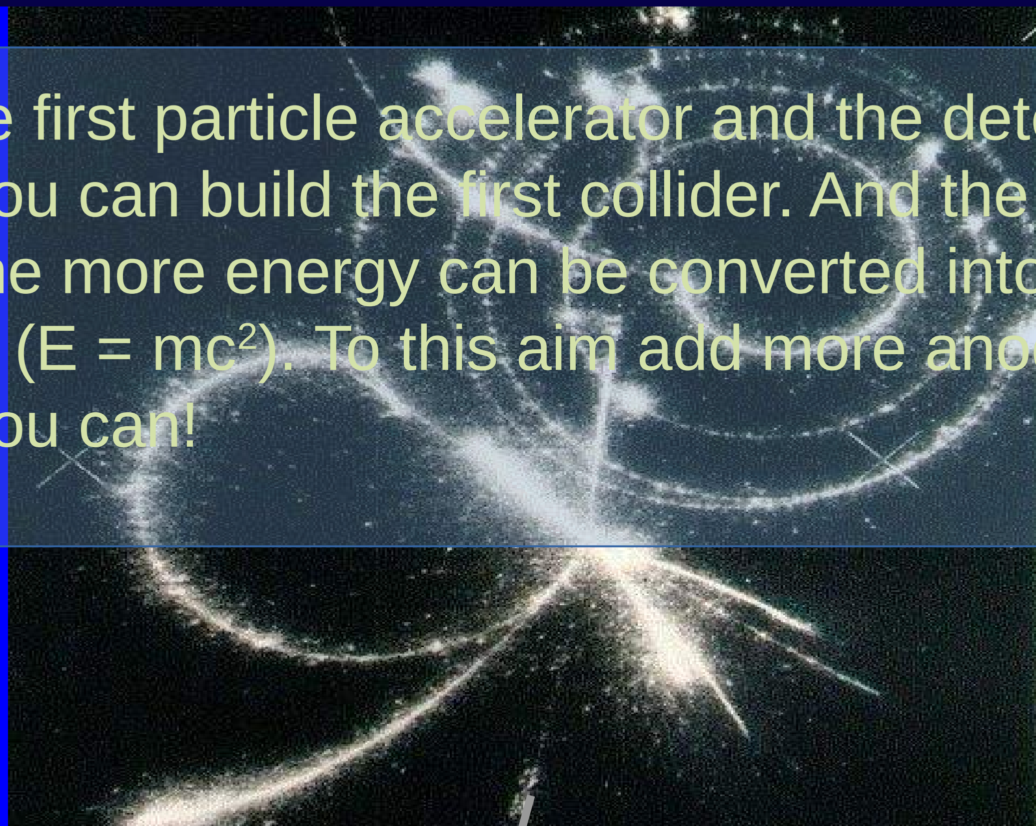
# Brief history of elementary particle discoveries

From the first particle accelerator and the detector chamber, ideally you can build the first collider.

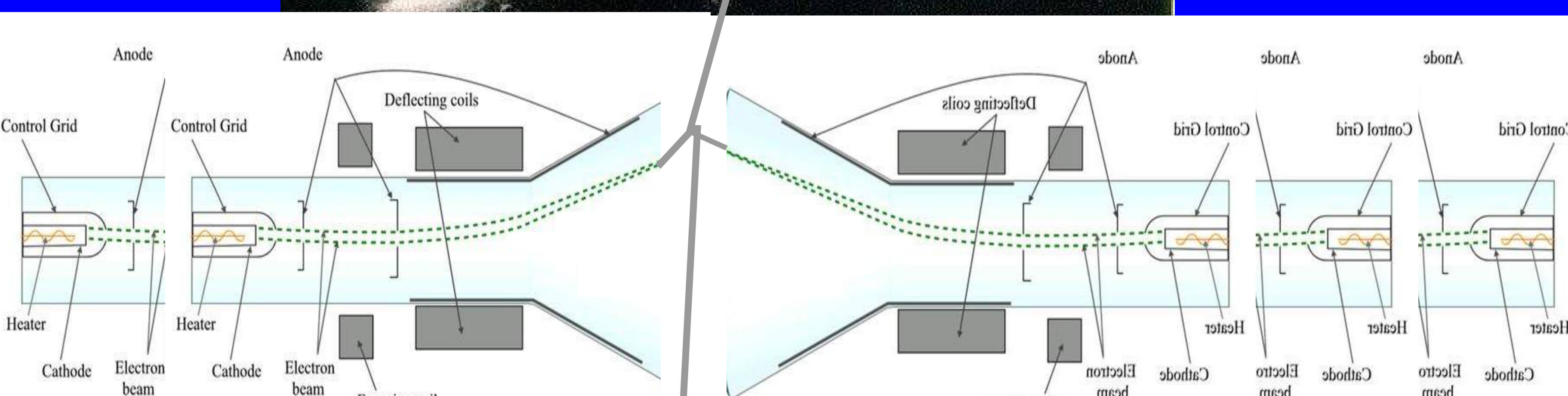




# Brief history of elementary particle discoveries

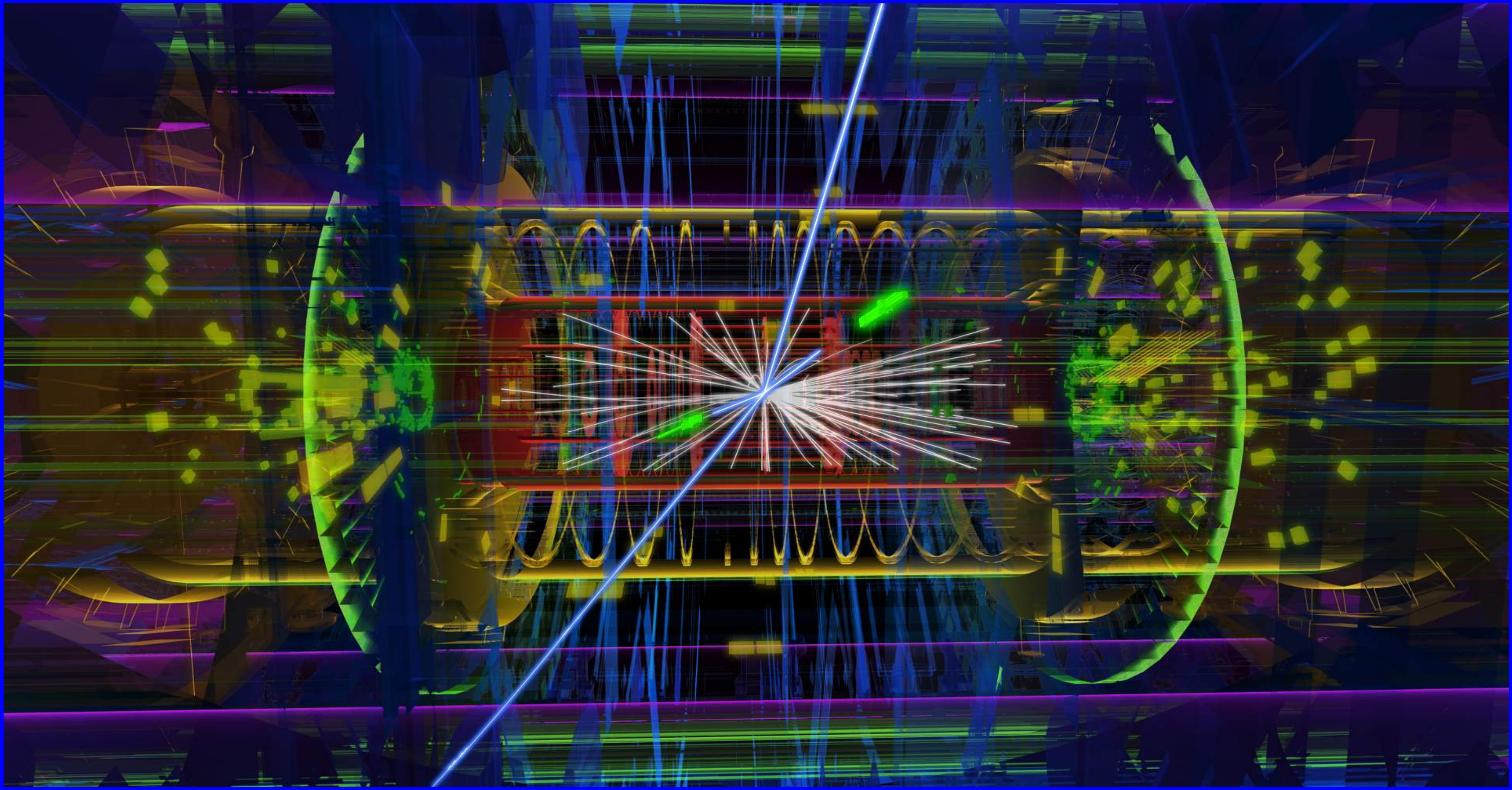


From the first particle accelerator and the detector chamber, ideally you can build the first collider. And the higher speed you reach, the more energy can be converted into unknown particles ($E = mc^2$). To this aim add more anode-cathode blocks you can!

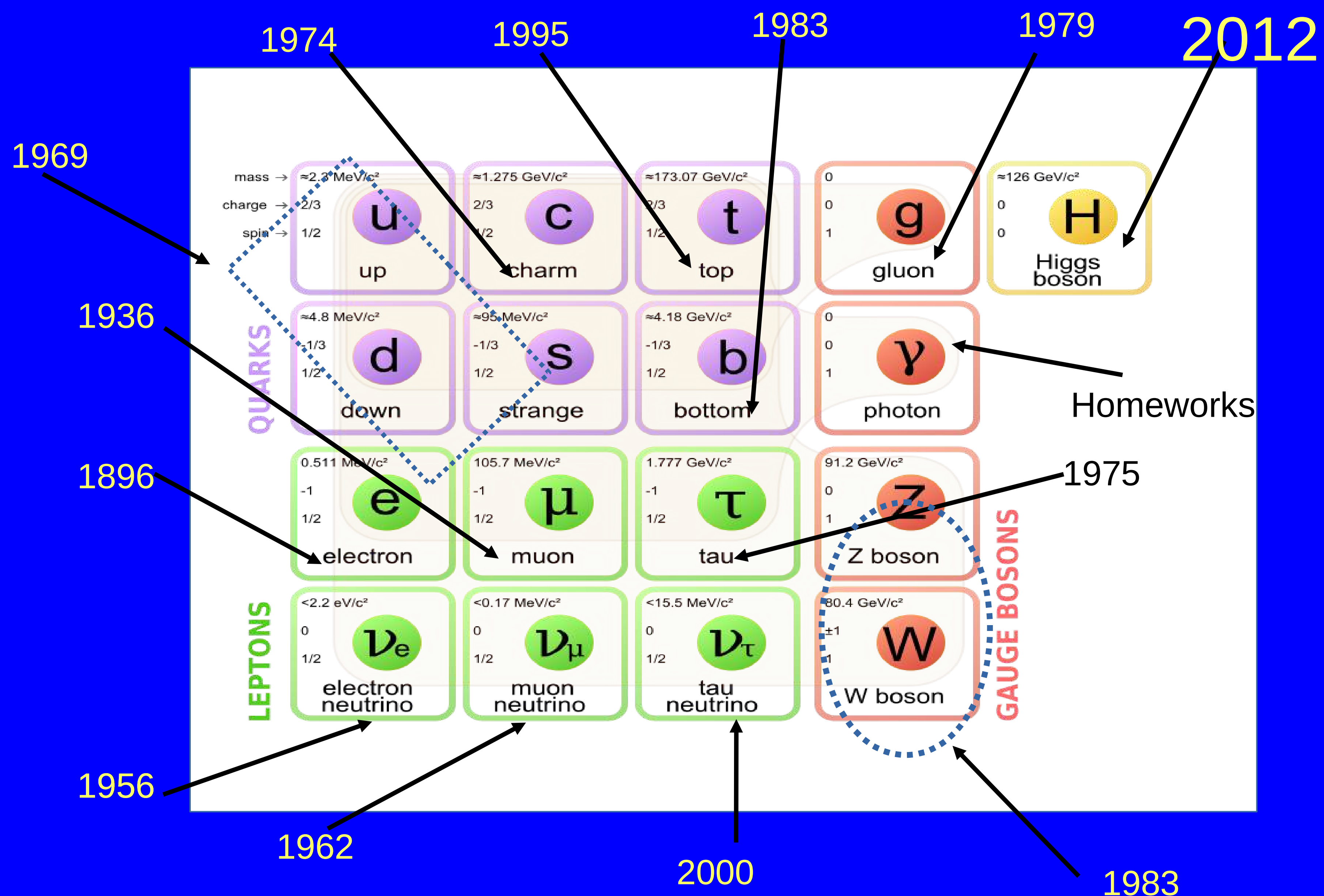


# Brief history of elementary particle discoveries

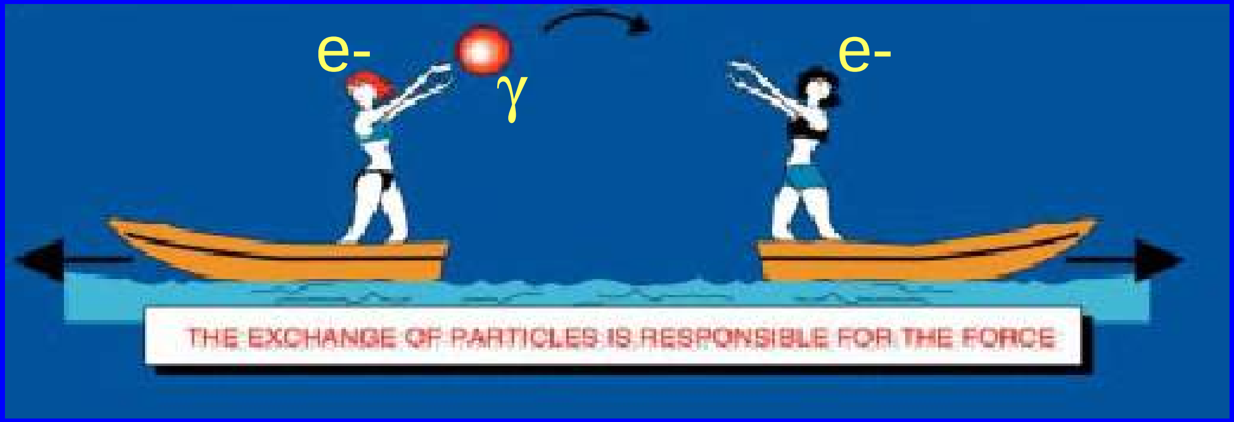
ATLAS: „pair“ of muons, „pair“ of electrons



# Brief history of elementary particle discoveries



# Forces (repulsive)

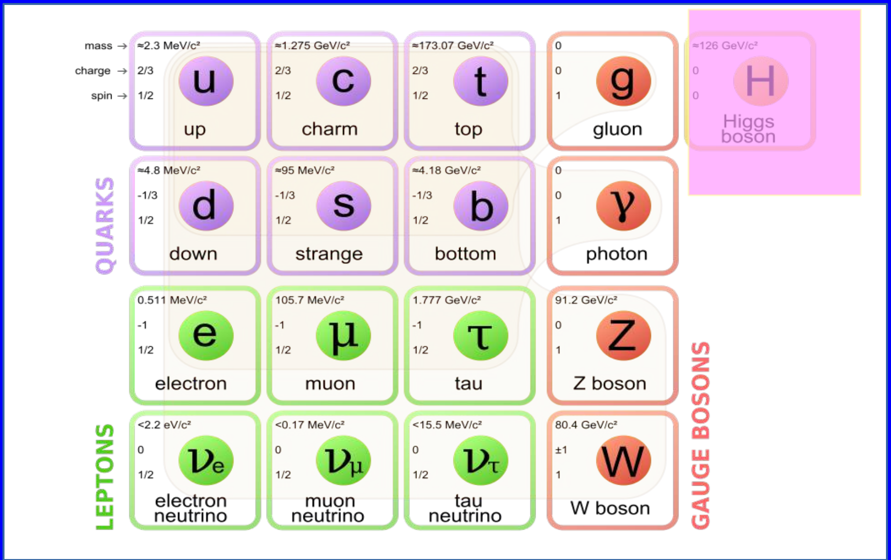



Gauge bosons mediate the forces:

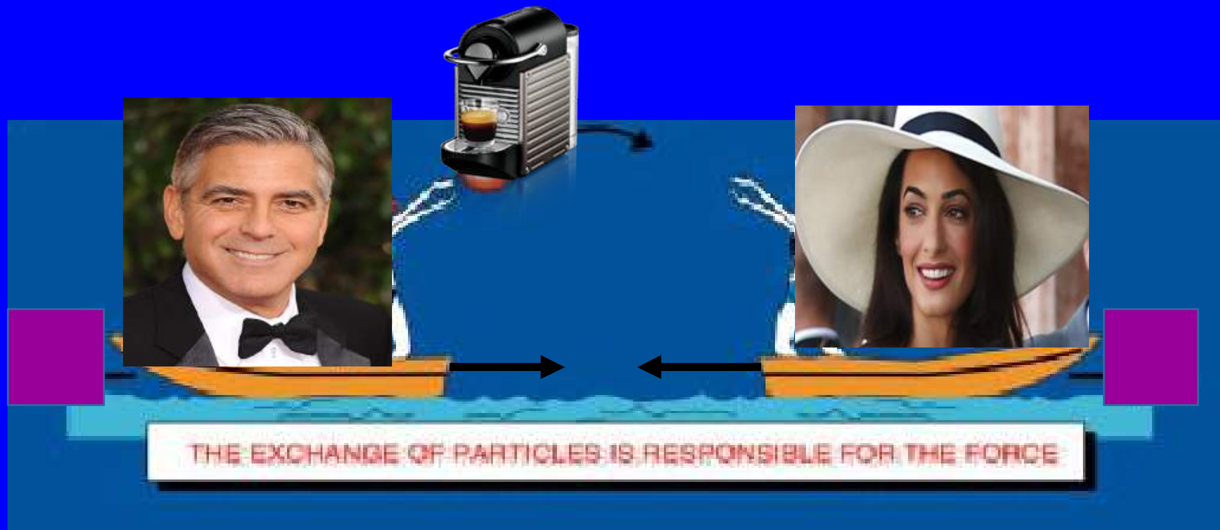
photons → electromagnetism

gluons → nuclear (strong) force

Z W bosons → weak force (radioactive decays)



# Forces (attractive)

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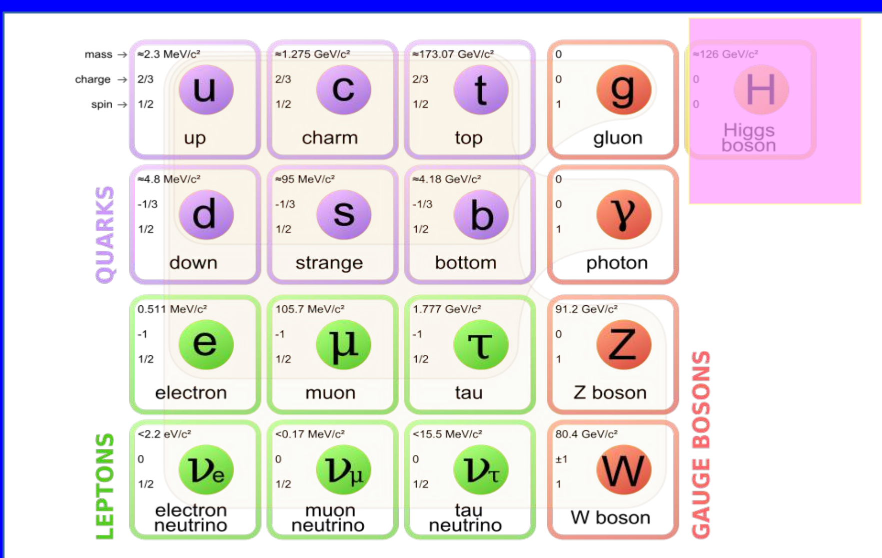

# The situation before 2012

From the study of all observed collisions and particle processes we understood that:

- Among quarks there is a very strong attractive force. They always stay together forming objects (hadrons) that have an integer charge (e.g.  proton = uud → Q = 1; neutron = ddu → Q=0)
- Leptons like staying alone, i.e. they do not form composite objects;
- Every time the quarks and/or the leptons interact, there is always a gauge boson;
- Quarks and leptons can be engrouped in 3 fam
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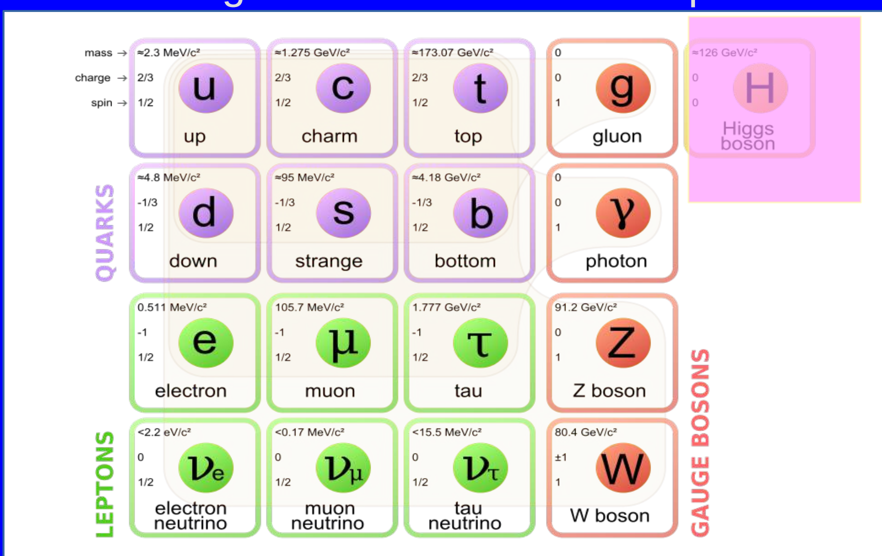
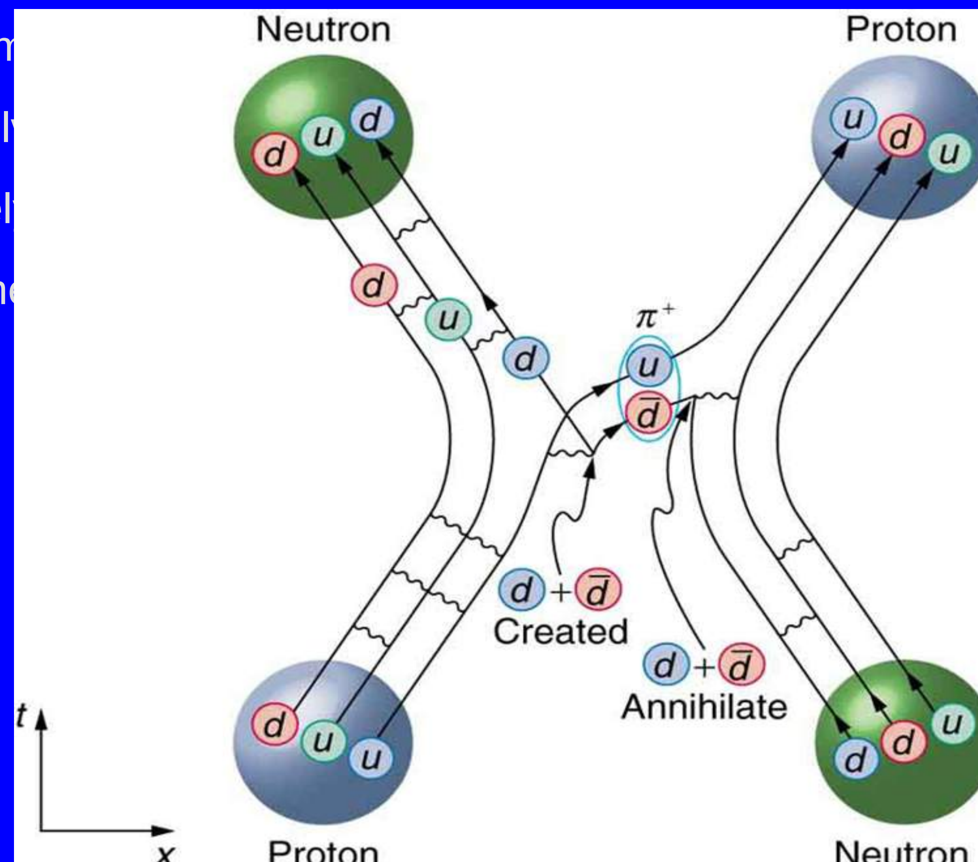
- The strenght of the interactions depends on the



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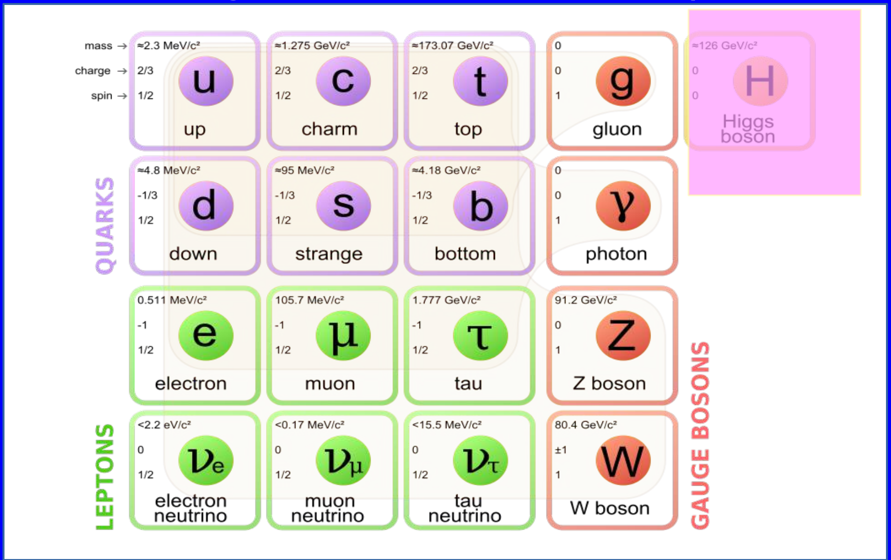


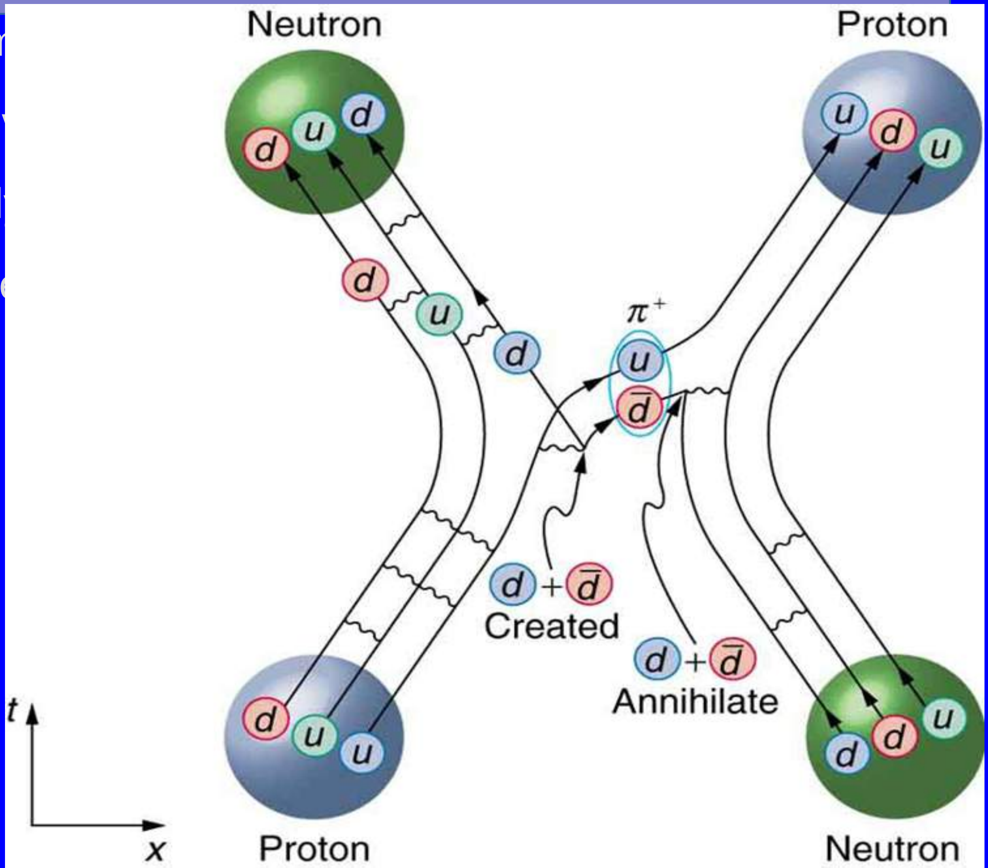

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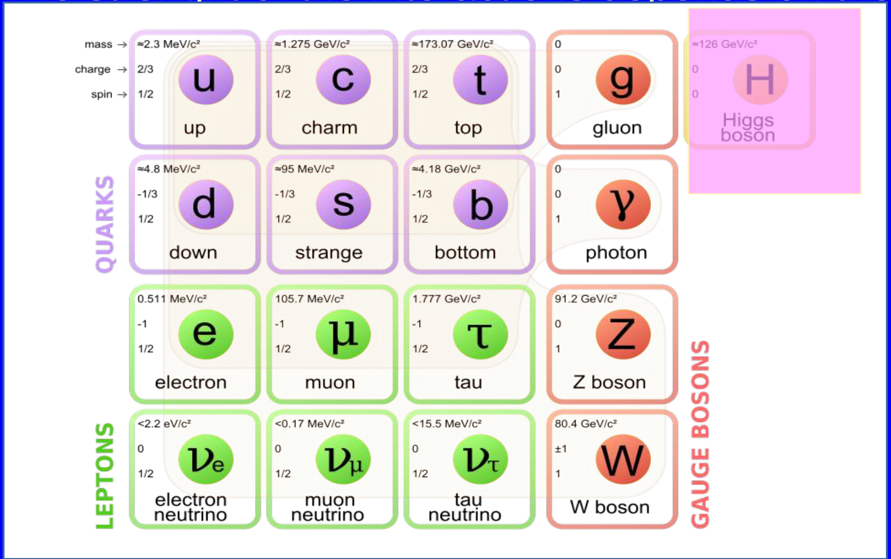


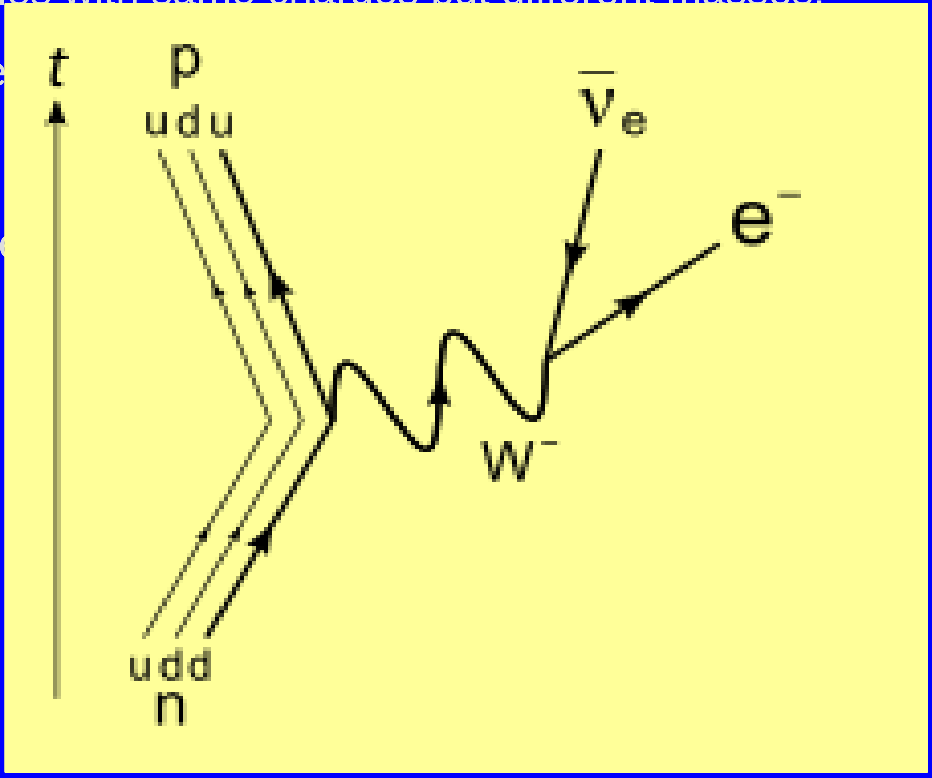

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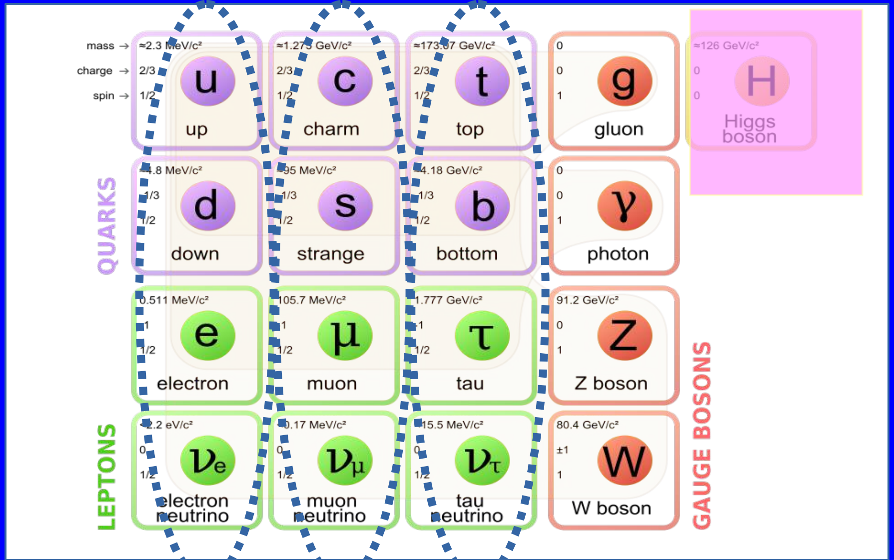

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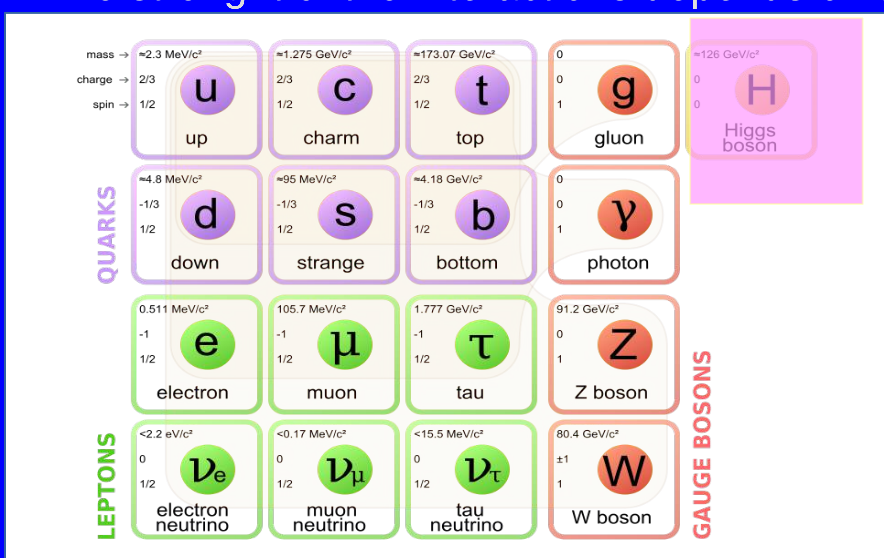


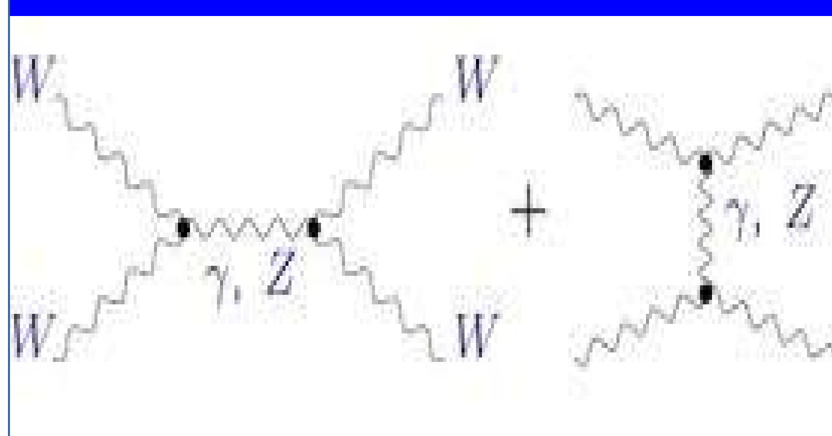

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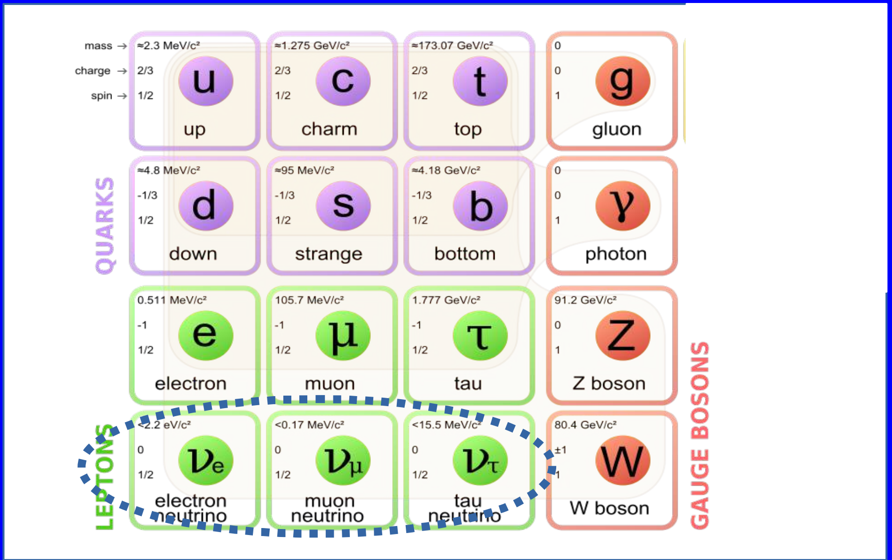

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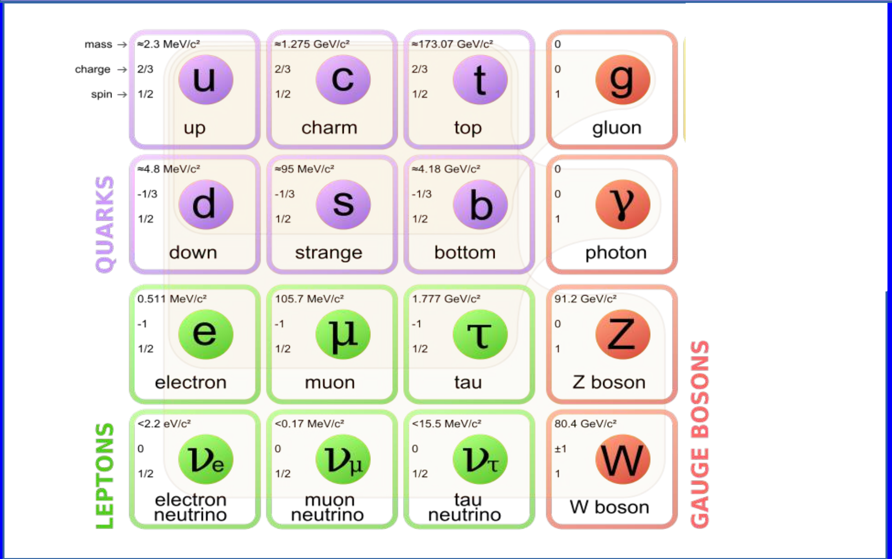


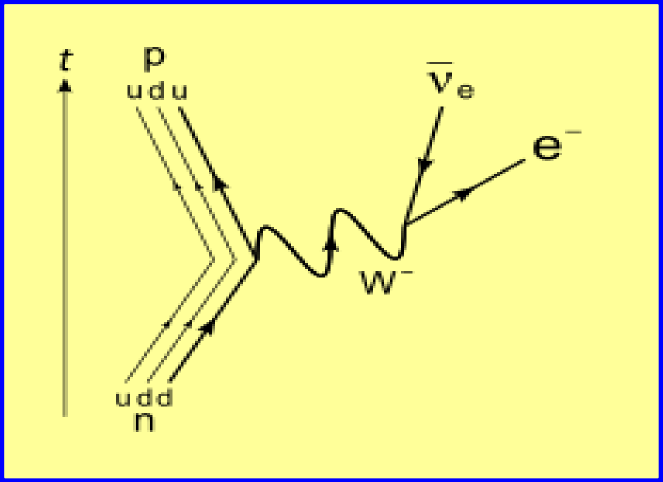

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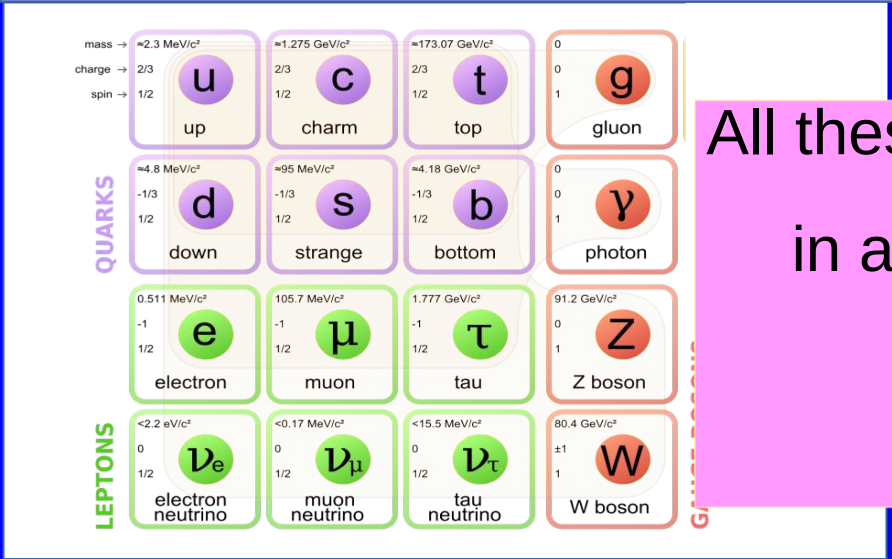
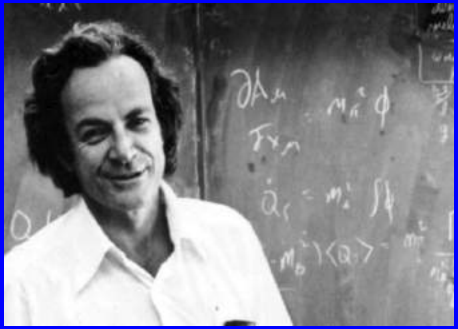



All these **facts** can be *precisely* described in a *deep, simple and beautiful* way:

<u>GAUGE THEORY</u>

# … simple and beautiful in other words ...

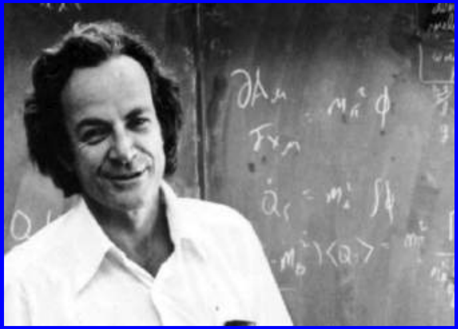


R. Feynman 1918-1988

“One way that's kind of a fun analogy to try to get some idea of what we're doing here to try to understand nature is to imagine that the gods are playing some great game like chess. Let's say a chess game. And you don't know the rules of the game, but you're allowed to look at the board from time to time, in a little corner, perhaps. And from these observations, you try to figure out what the rules are of the game, what [are] the rules of the pieces moving.

You might discover after a bit, for example, that when there's only one bishop around on the board, that the bishop maintains its color. Later on you might discover the law for the bishop is that it moves on a diagonal, which would explain the law that you understood before, that it maintains its color. And that would be analogous we discover one law and later find a deeper understanding of it.

# … simple and beautiful in other words …

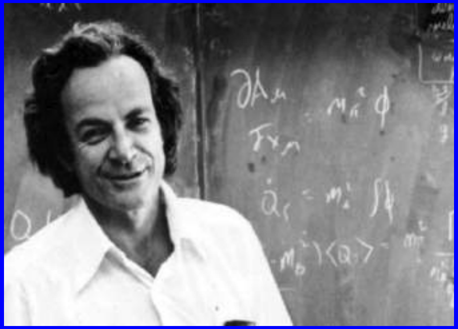


R. Feynman 1918-1988

…. Ah, then things can happen--everything's going good, you've got all the laws, it looks very good--and then all of a sudden some strange phenomenon occurs in some corner, so you begin to investigate that, to look for it. It's castling--something you didn't expect.

We're always, by the way, in a fundamental physics, always trying to investigate those things in which we don't understand the conclusions. We're not trying to all the time check our conclusions; after we've checked them enough, they're okay. The thing that doesn't fit is the thing that's most interesting--the part that doesn't go according to what you'd expect.

# … simple and beautiful in other words ...

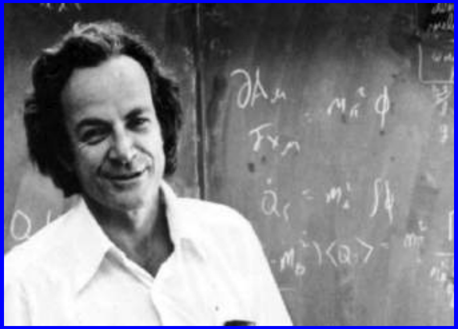


R. Feynman 1918-1988

… Also we can have revolutions in physics. After you've noticed that the bishops maintain their color and that they go along on the diagonals and so on, for such a long time, and everybody knows that that's true; then you suddenly discover one day in some chess game that the bishop doesn't maintain its color, it changes its color. Only later do you discover the new possibility that the bishop is captured and that a pawn went all the way down to the queen's end to produce a new bishop. That could happen, but you didn't know it.

And so it's very analogous to the way our laws are. They sometimes look positive, they keep on working, and all of a sudden, some little gimmick shows that they're wrong--and then we have to investigate the conditions under which this bishop changed color... happened... and so on... And gradually we learn the new rule that explains it more deeply.

# … simple and beautiful in other words ...



R. Feynman 1918-1988

… Unlike the chess game, though... In the case of the chess game, the rules become more complicated as you go along, but in the physics when you discover new things, it becomes more simple. It appears on the whole to be more complicated, because we learn about a greater experience; that is, we learn about more particles and new things, and so the laws look complicated again. But if you realize that all of the time, what's kind of wonderful is that as we expand our experience into wilder and wilder regions of experience, every once in a while we have these integration in which everything is pulled together in a unification, which it turns out to be simpler than it looked before.”

All these **facts** can be *precisely* described

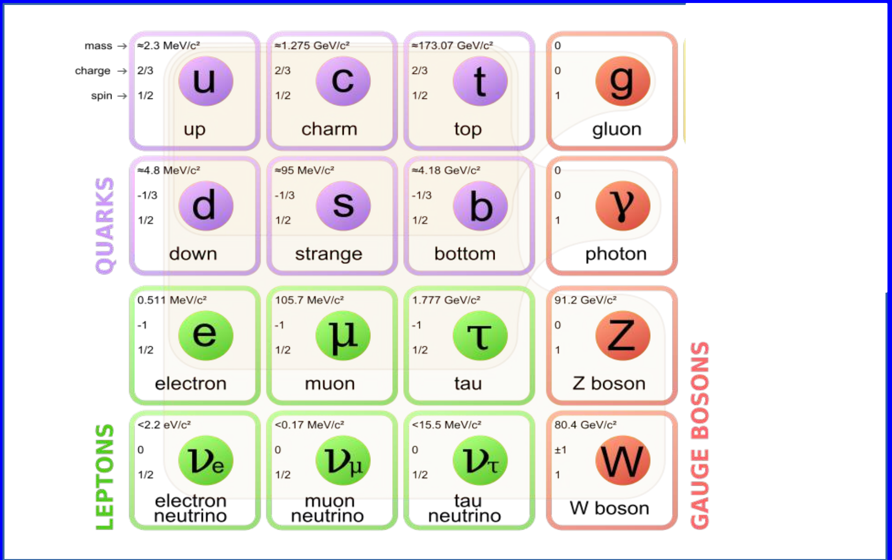
in a *deep, simple and beautiful* way:

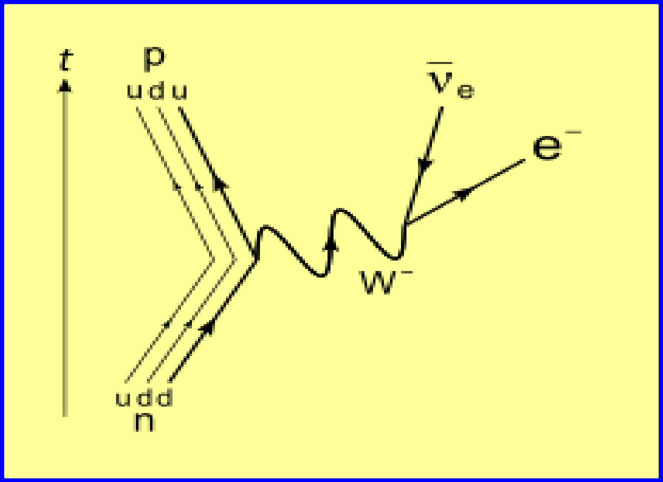
GAUGE THEORY

# The situation before 2012

- In a gauge theory there is not only the electric charge. Further charges exist.
- Leptons and quarks have these charges. Gauge bosons also have these charges.
- An interaction is allowed only if all these charges are conserved.

- In a more technical language, there are some „symmetries“ in Nature. These symmetries are called “gauge symmetries”. From these you can derive the rules that the particles follow when they interact.



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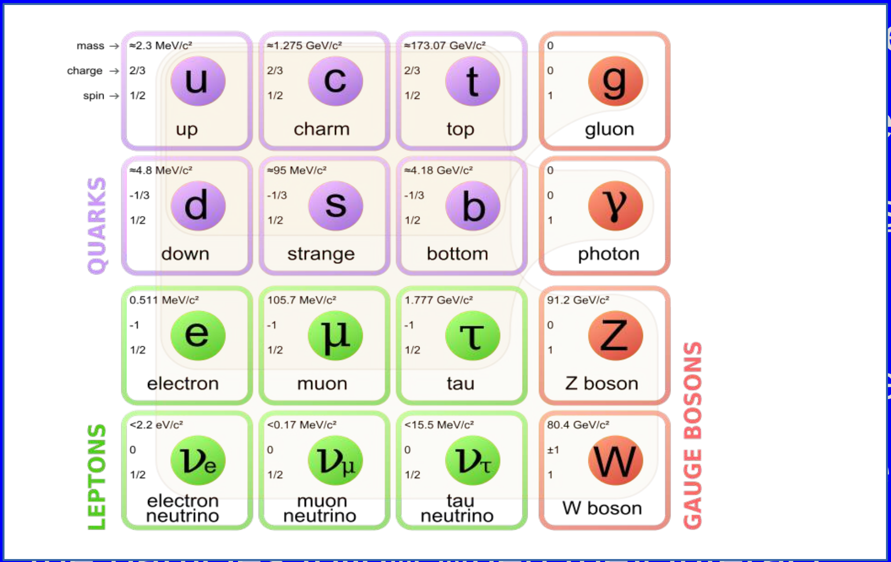


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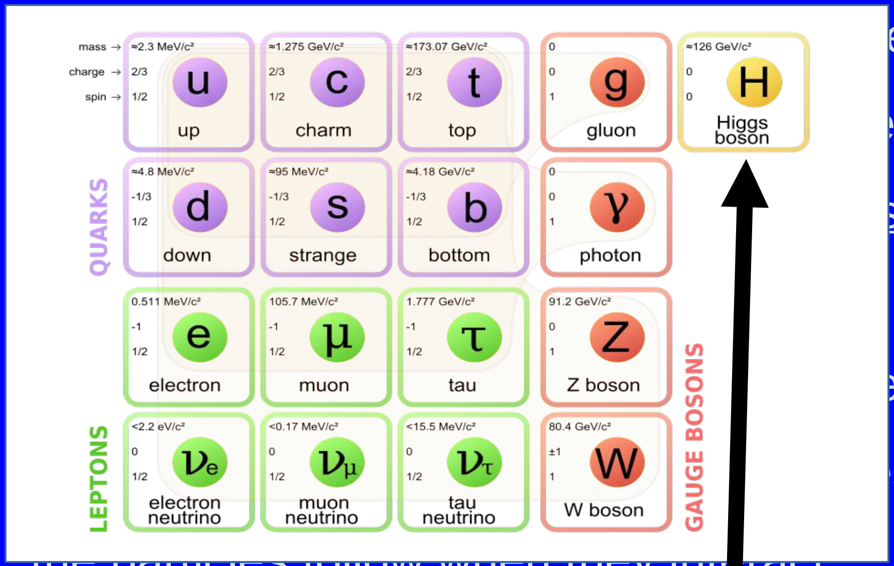
## BIG PROBLEM (no mass)

The gauge theory is wonderful, but when you try to assign the charges to the discovered particles you realize that

*<u>THESE PARTICLES CANNOT HAVE A MASS</u>*

# The situation before 2012

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BIG PROBLEM (no mass)

The problem is avoided if there is a hidden particle:

THE HIGGS BOSON

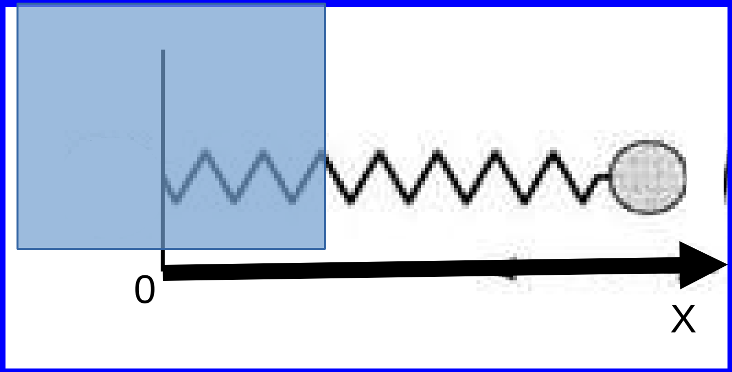
# The role of the Higgs boson

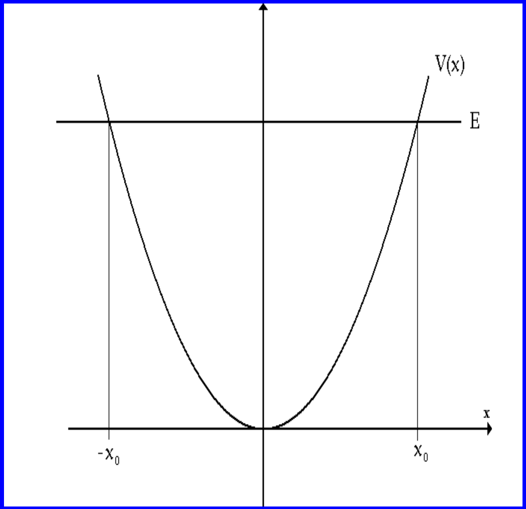
- Let's try to understand the role of the Higgs boson in a qualitative way.
- Consider a harmonic oscillator. Its motion can be implicitly described by a Lagrangian

$$L = E_K - V = \frac{1}{2} m_x \left(\frac{dx}{dt}\right)^2 - \frac{1}{2} k_x x^2$$

$$p_x = \frac{\partial L}{\partial (dx/dt)} = m_x \frac{dx}{dt} \quad ; \quad F_x = \frac{\partial L}{\partial x} = -k_x x$$

$$\omega_x = \sqrt{k_x / m_x} \qquad x(t) = A \cos(\omega_x t)$$




How would you measure $\omega_x$ ?

$$f_x = \omega_x / (2\pi)$$

# The role of the Higgs boson

- We add a second oscillator Y that does NOT interact with the oscillator X
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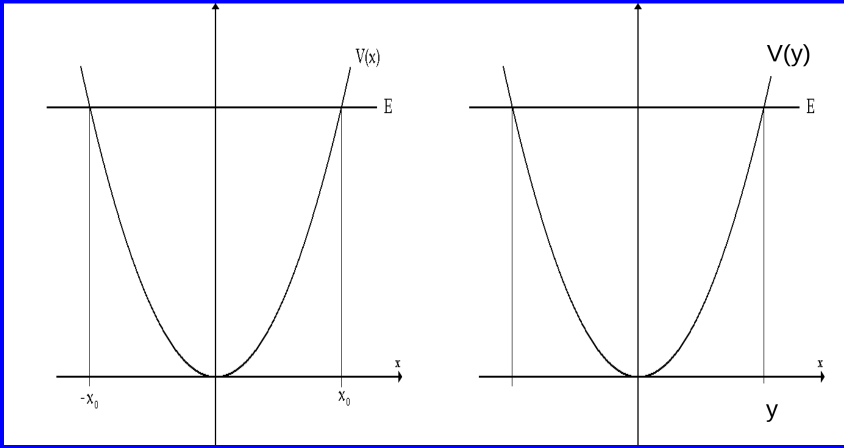


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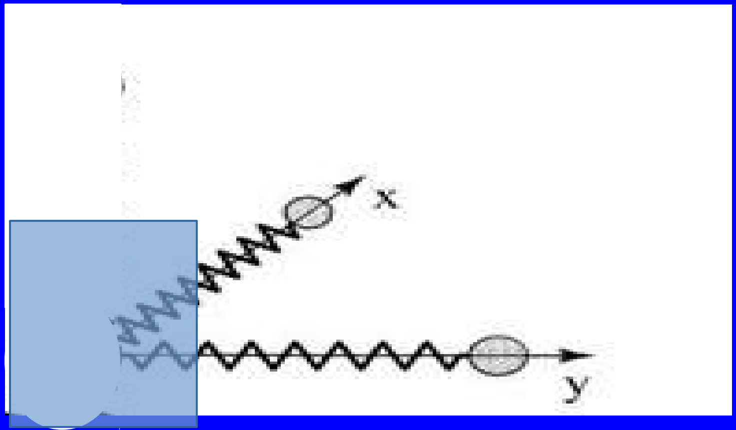


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# The role of the Higgs boson

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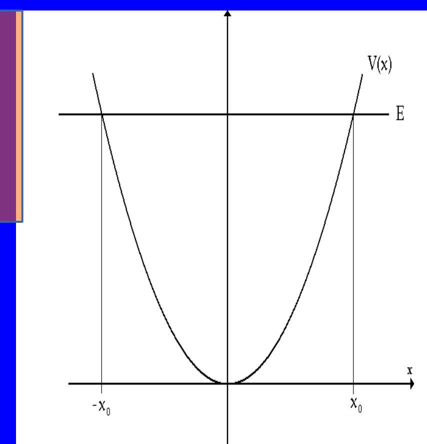


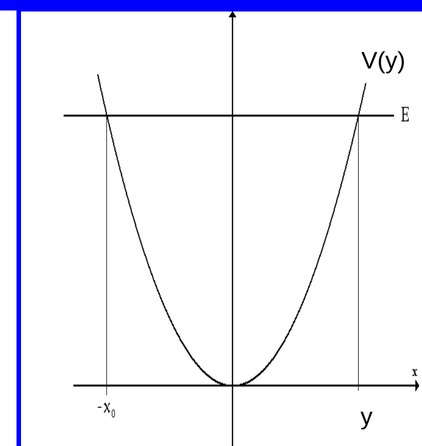


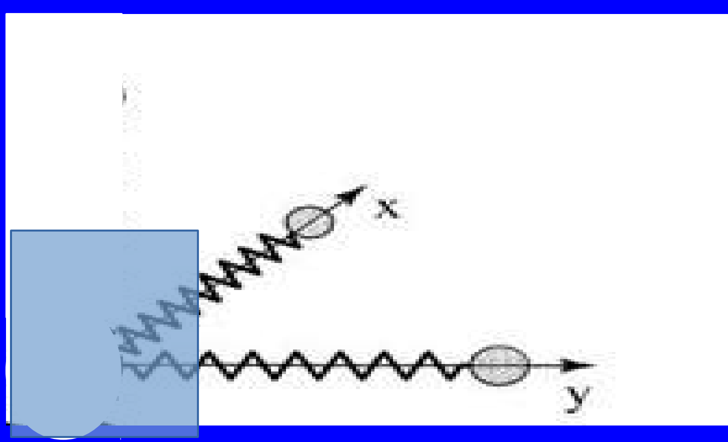

# The role of the Higgs boson

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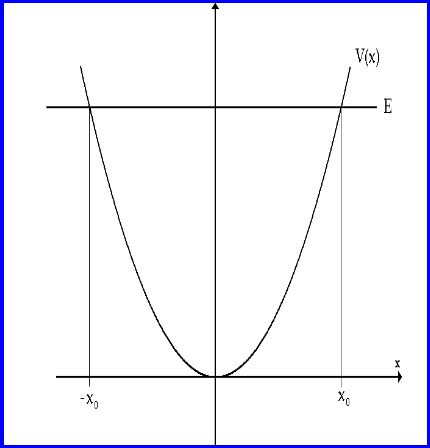


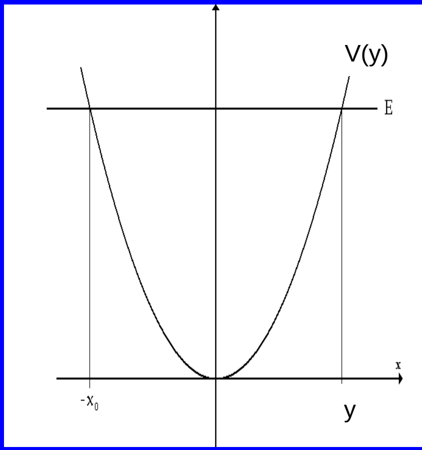


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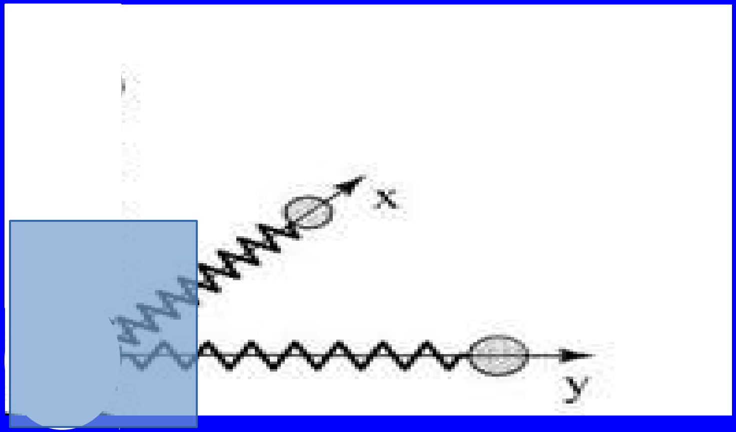


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# The role of the Higgs boson

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$$k_x^{eff} = k_x + g_x \, const$$

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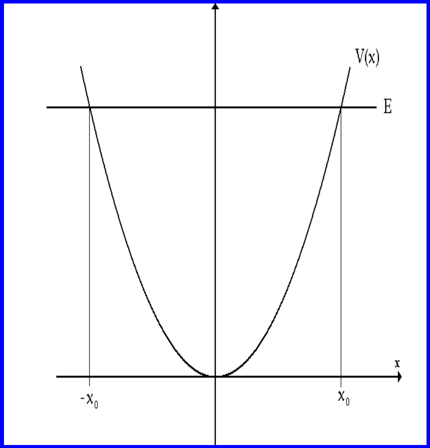


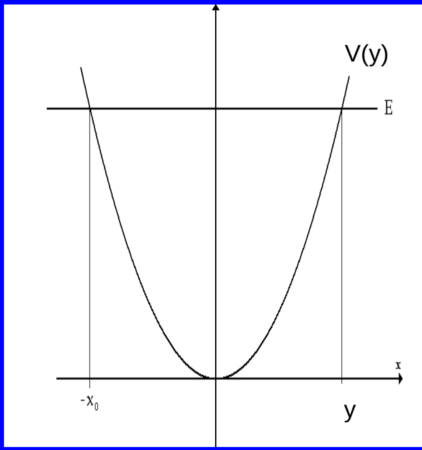


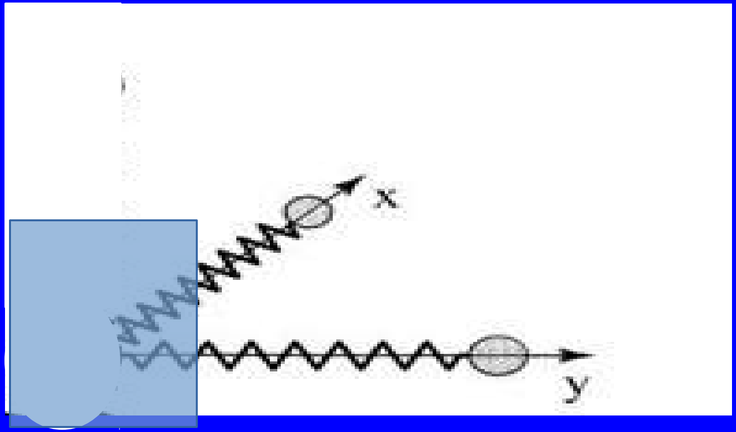


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*Even if you could not write the term $k_x x^2$, the object X still behaves as a harmonic oscillator with $k_x^{eff}$.*

*You just need the object Y (which you might have not seen) having an (almost) constant value !!!*

# The role of the Higgs boson

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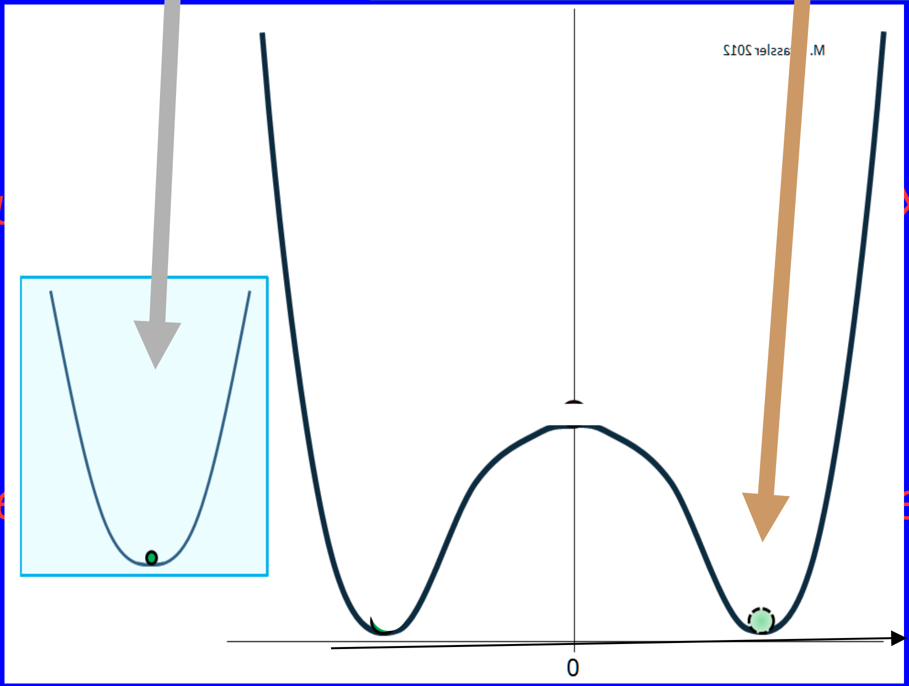
$$k_x^{eff} = k_x + g_x\, const$$

$$f_x^{eff} = \sqrt{k_x^{eff} / m_x / (2\pi)}$$

*Even if you co* … *X still behaves*




*You just ne* … *e not seen)*

# The Higgs prediction (mass in gauge theory)

There is a strong similarity between the harmonic oscillators and the particles:

- Each already-known particle is the harmonic oscillator X
- There is an undiscovered particle (Higgs) which is the harmonic oscillator Y
- There is an interaction proportional to $g_x$ between X and Y
- This interaction generates an effective mass, like in the oscillator case:

$$k_x^{eff} = k_x + g_x\, const \longrightarrow m_x^{eff} = m_x + g_x\, const$$

- The beautiful gauge symmetry forbids the mass term, i.e. it imposes $m_x = 0$ , thus all particles have masses proportional to the constant „const”. This means

$$m_x^{eff} = g_x\, const \qquad m_z^{eff} = g_z\, const \qquad m_\ell^{eff} = g_\ell\, const$$

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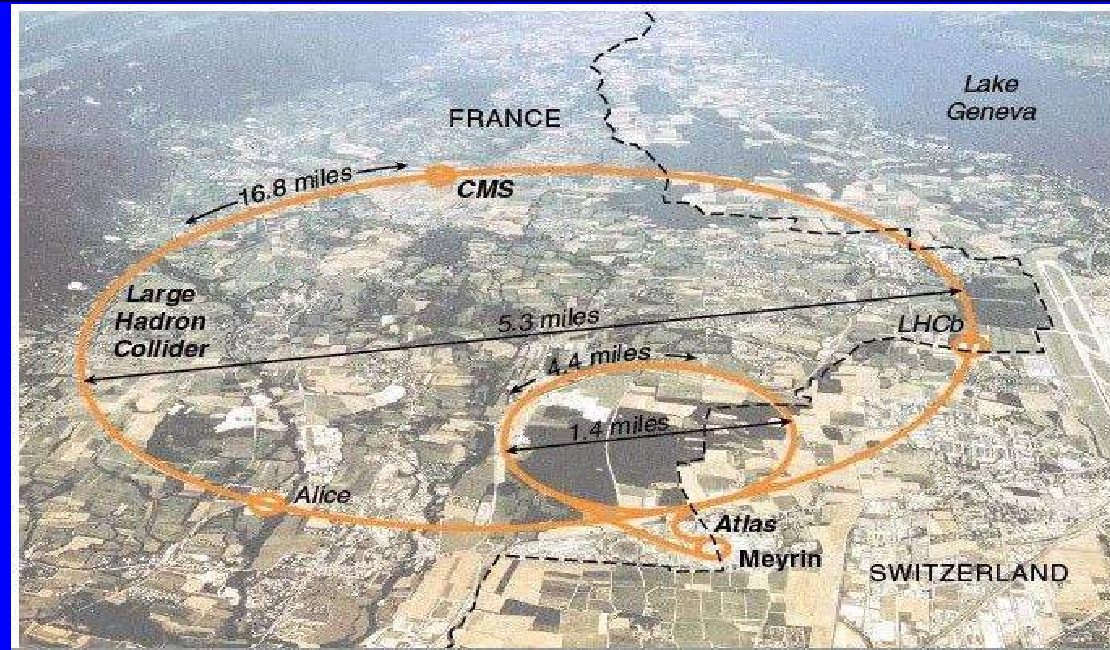
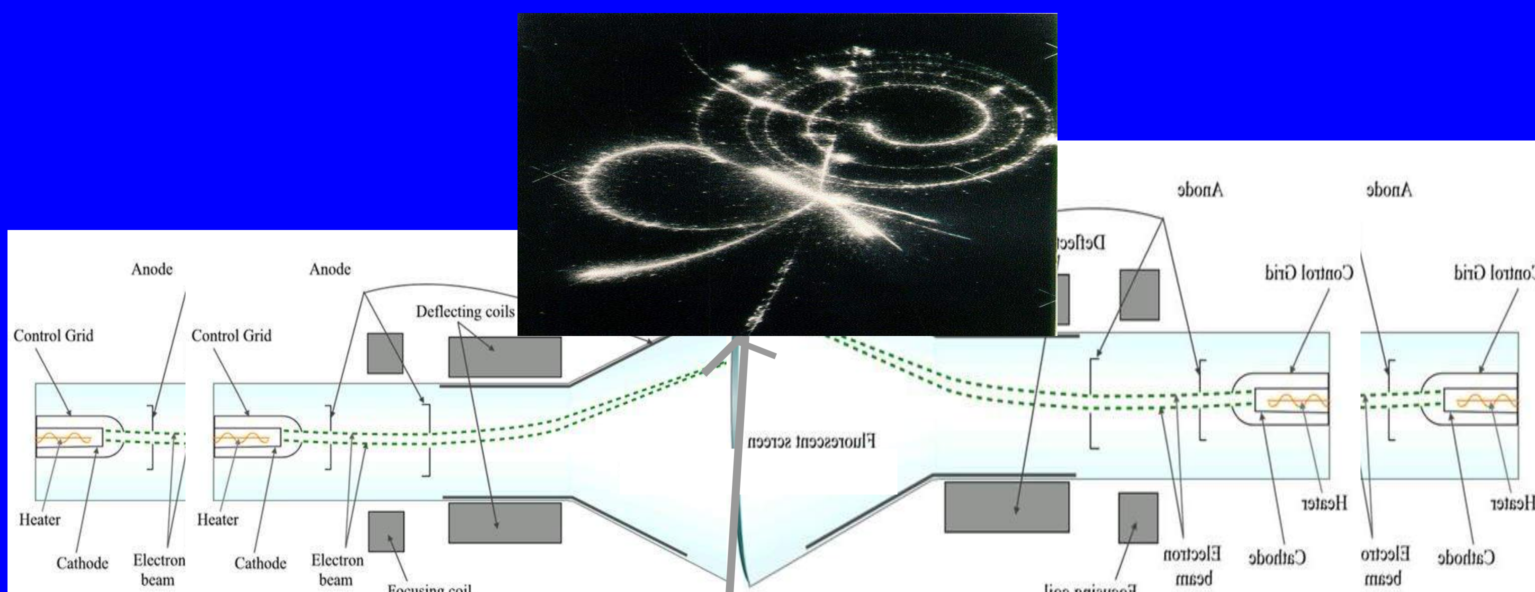
If you plot the couplings as a function of the masses, what does the plot look like?

# LHC measurements

1 mile ≈ 1.6 Km



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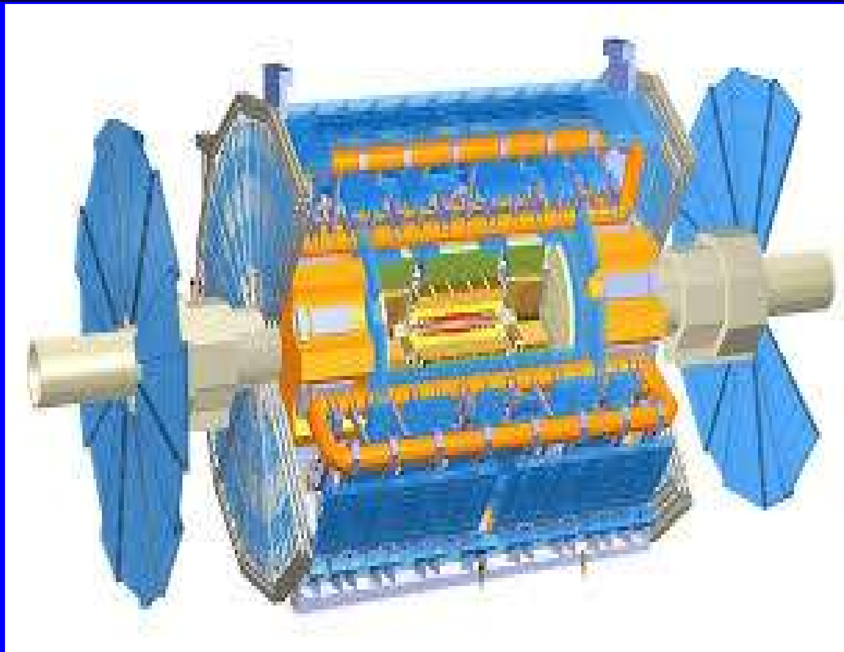

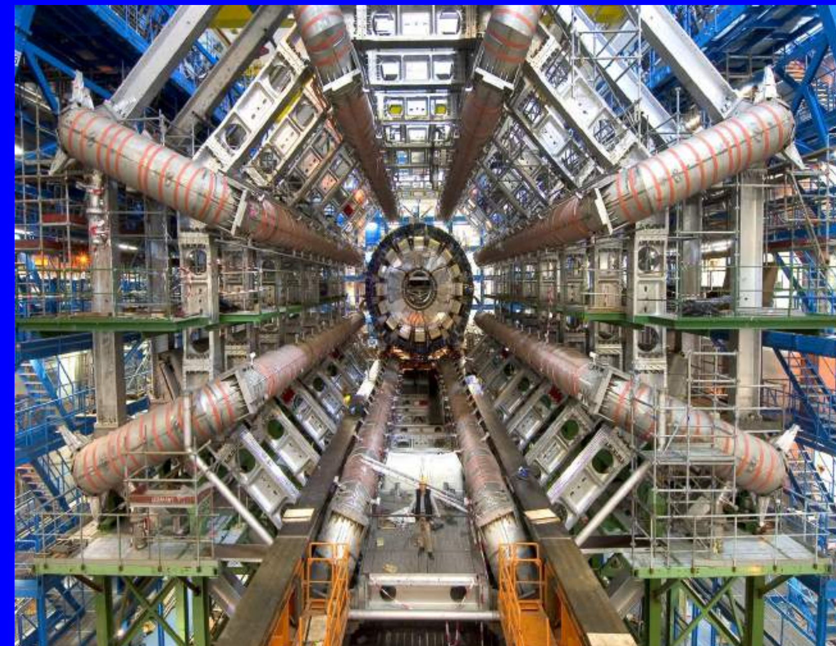

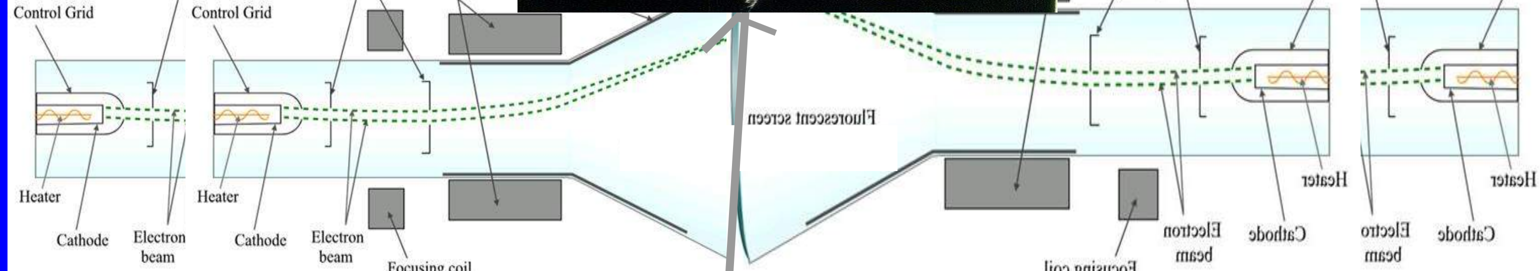

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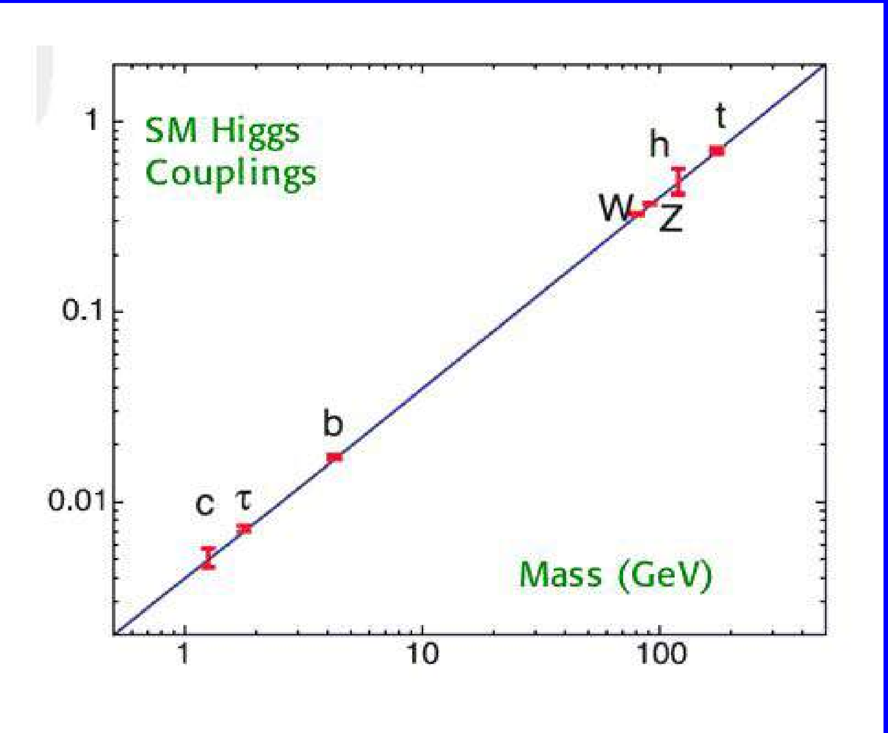


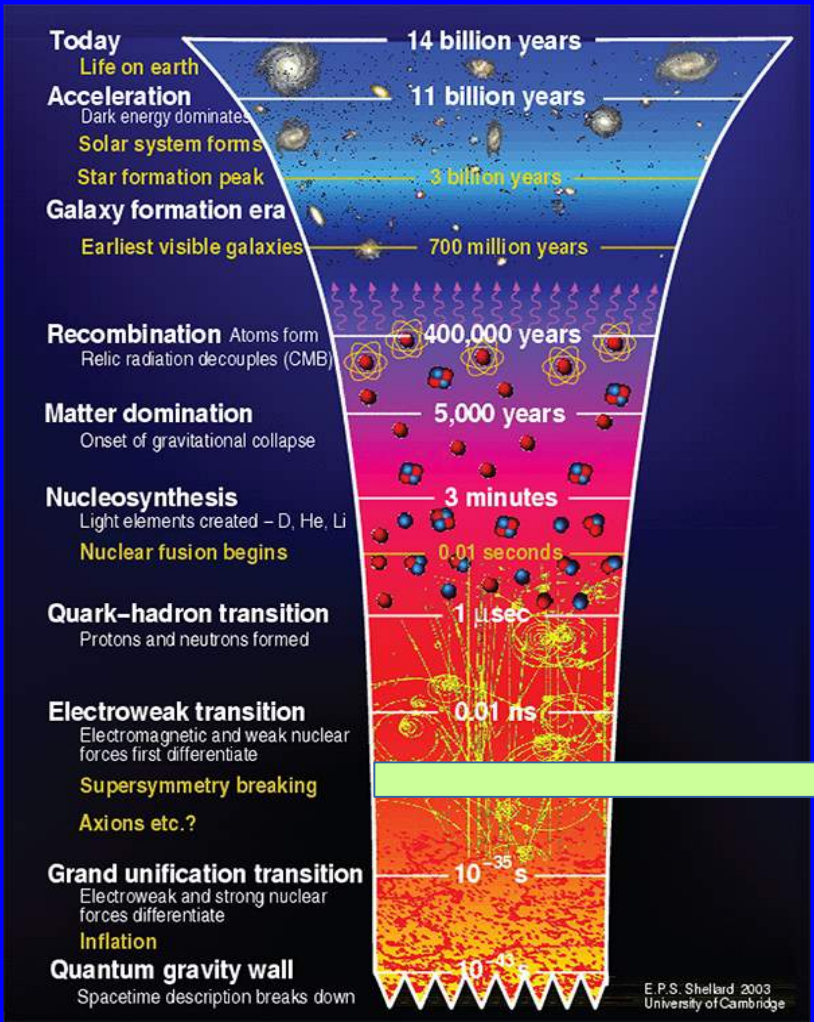
# LHC measurements

- Eventually, everybody agreed that the observation was the discovery of the particle so-long-ago predicted

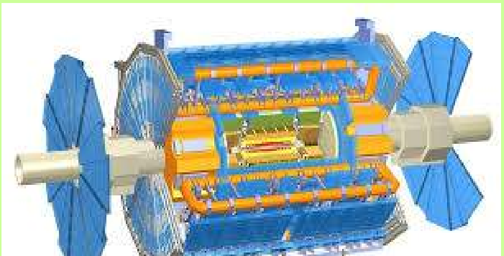
# Summary of the FACTS

| Temp.[K] | Density [gr/cm$^3$] | Energy [GeV] | Size |
|---|---|---|---|
| 1 | $10^{-30}$ | $10^{-12}$ | 1 |
| $10^3$ | $10^{-21}$ (>atom) | $10^{-9}$ | $10^{-3}$ |
| $10^{10}$ | 10 (>water) | $10^{-3}$ | $10^{-9}$ |
| $10^{15}$ | $10^{28}$ | $10^3$ | $10^{-15}$ |

?

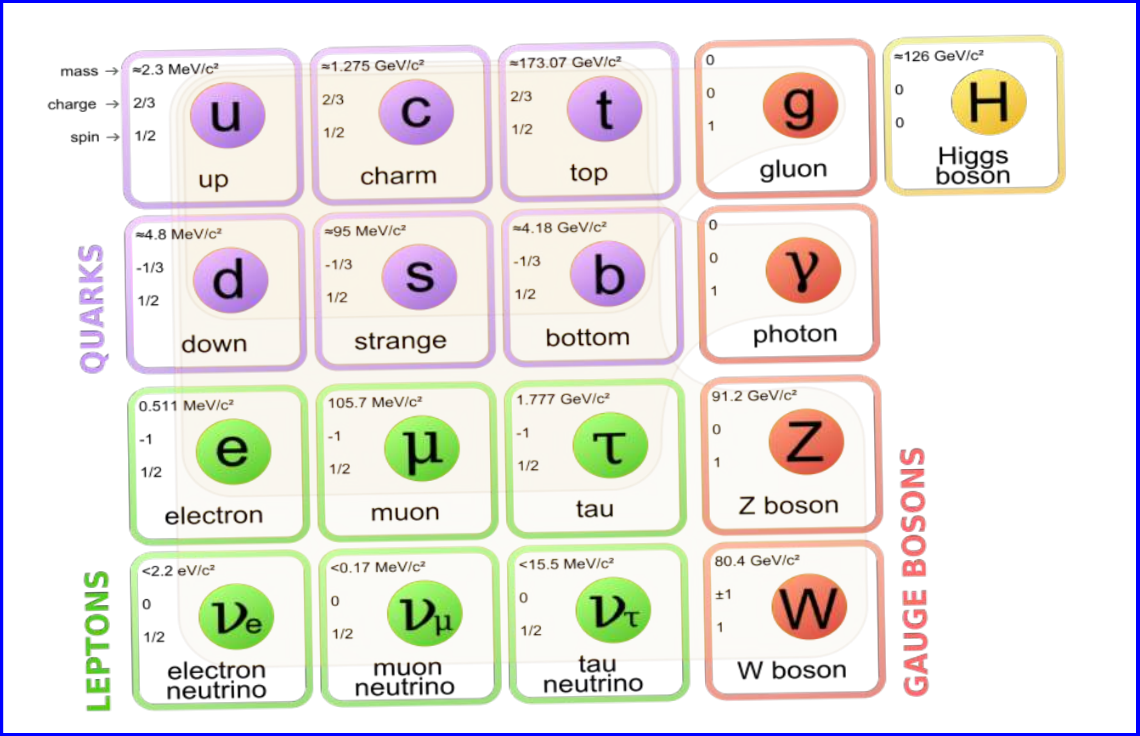



LHC



# Summary of the FACTS

- We know that there exist (at least) these elementary particles:

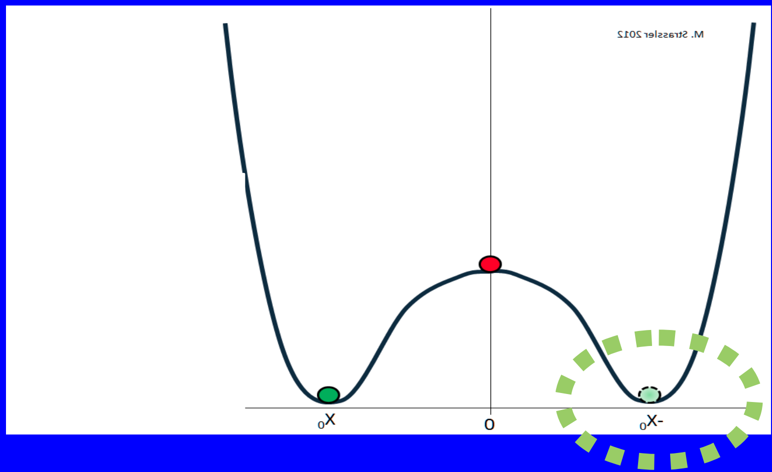



- These particles have a mass due to the interaction with the Higgs.

The larger the interaction, the larger the mass

# Summary of the FACTS

- The Higgs boson (at present) has this kind of potential




- We do not know how the Higgs potential was in early Universe:

1) Its behaviour when the Universe was very hot

2) Its behaviour when the energy involved in the early Universe was much larger than the one we can test at the LHC

# Inferring / Speculating

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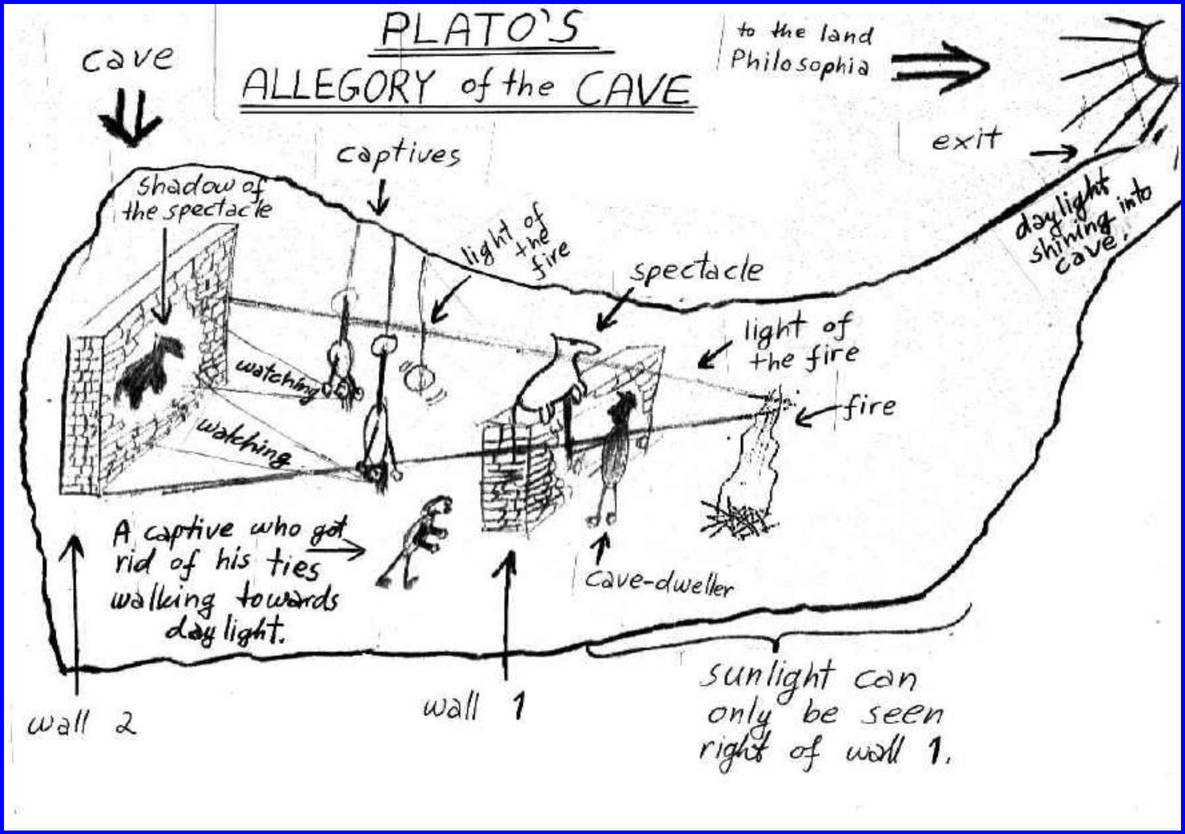
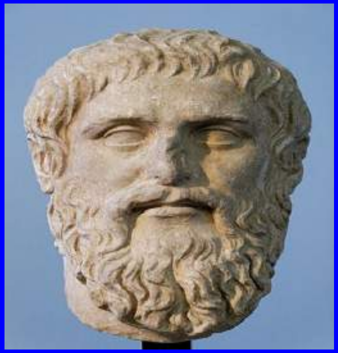
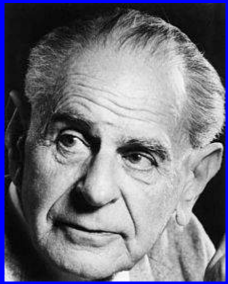


Plato 428-348 b.c.

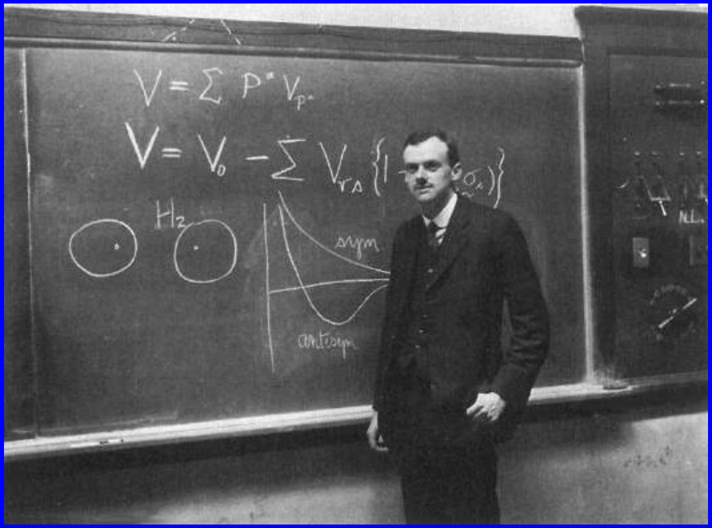
Making some assumptions, we use the Higgs boson and its potential to solve some deep problems in cosmology

Our trust on the assumptions increases
if they lead us to make PREDICTIONS



# Back again: Antimatter

In 1928 Paul Dirac predicted the existence of antimatter, when he tried to unify Schrödinger's and Heisenberg's quantum mechanics with Einstein's special relativity




Paul Dirac 1902-1984

Dirac equation:

$$i\gamma^{\mu}\partial_{\mu}\psi - m\psi = 0$$

$$\psi = (\psi_1, \psi_2, \psi_3, \psi_4)$$

This equation describes 4 states:
2 with negative charge (electron: spin ±½)
2 with positive charge (spin ±½)
→ anti-electron = positron

# The positron

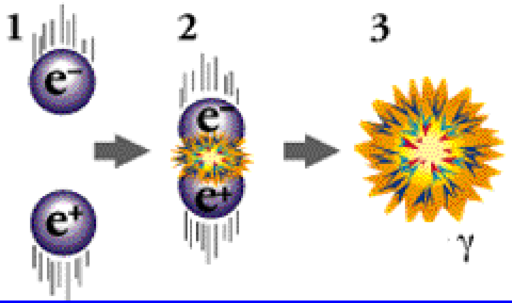
The negative charge solutions to the Dirac equation describe the hydrogen atom better than 1 part in a million → cannot be complete nonsense!

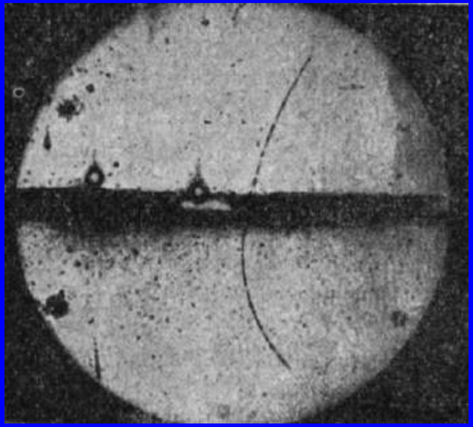
What about the mysterious positive charge solutions??

1932 Carl Anderson discovered the positron when studying cosmic rays

The positron has exaclty the same mass as the electron but opposite (gauge) charges  (e.g. the electric charge)

Electrons and positrons annihilate into photons ($E=mc^2$)

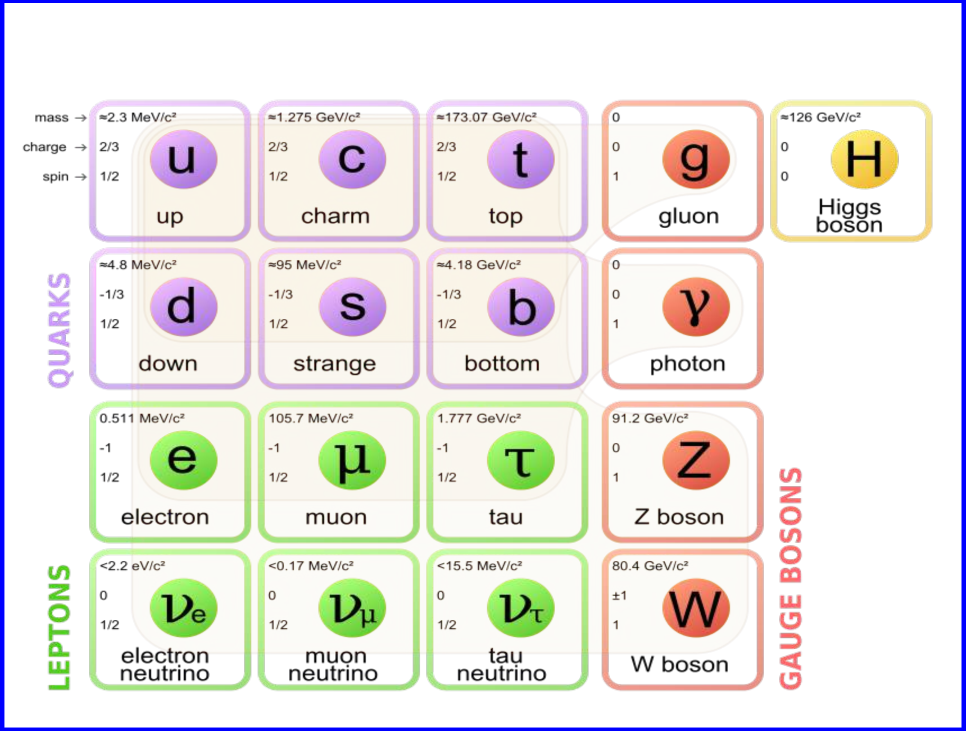


positron going through a cloud chamber

# All particles have antiparticles

Antiparticles have: the same mass
opposite charges



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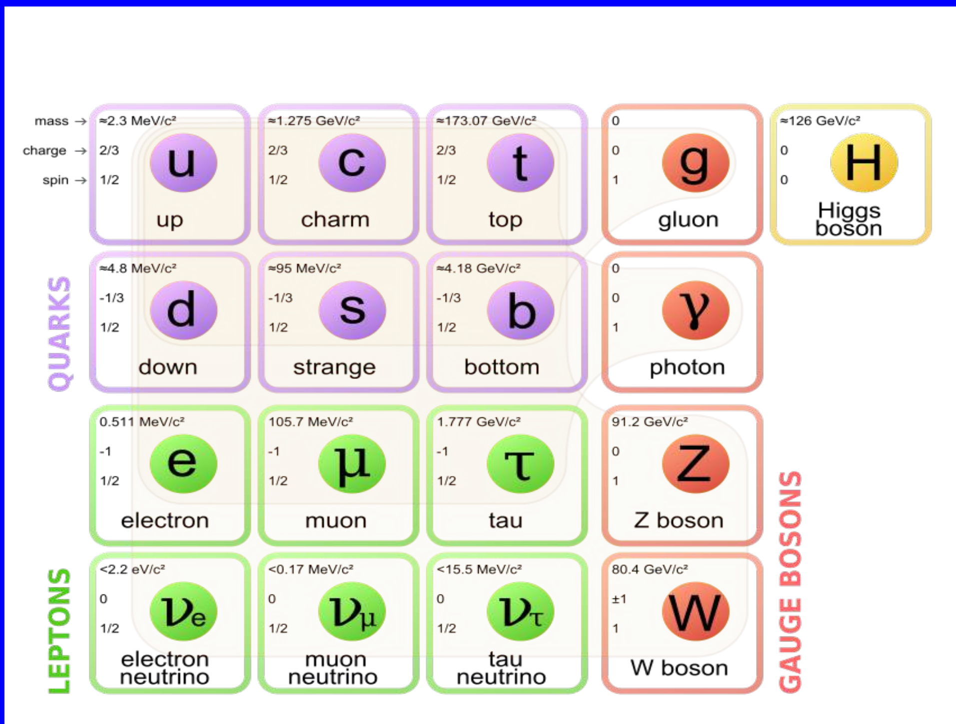
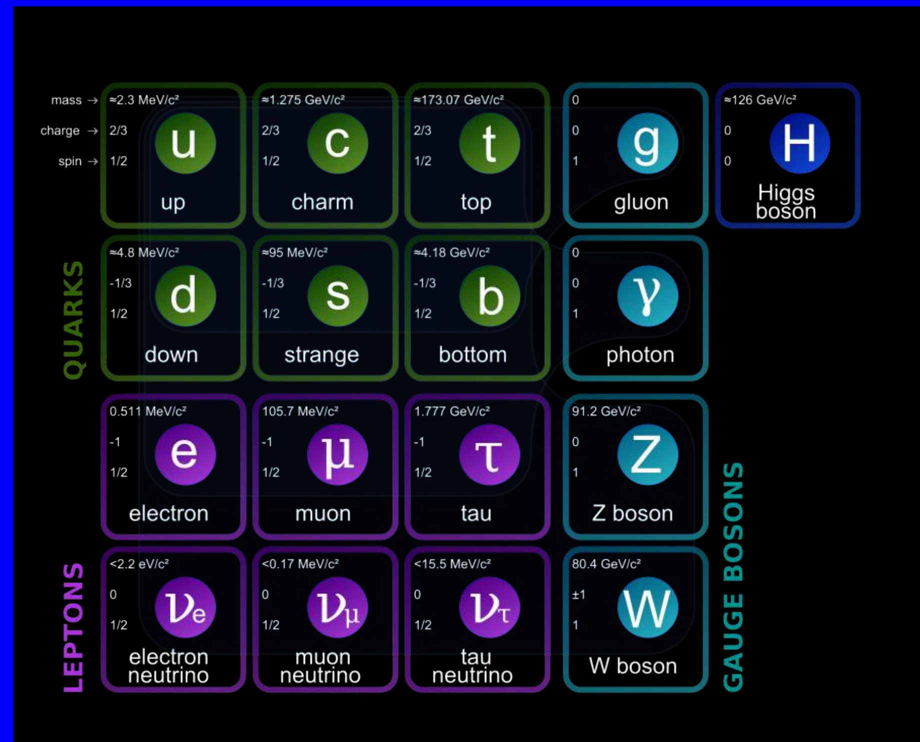



Examples: electron – positron

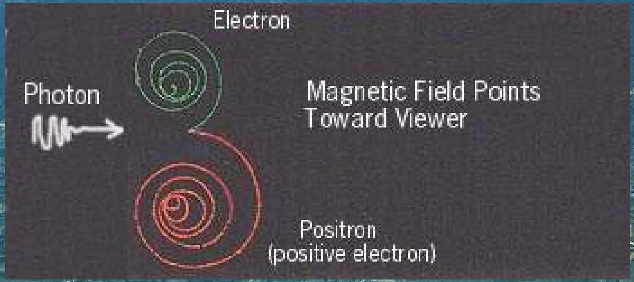
proton – antiproton

up-quark – anti-up quark

photon – photon (its own antiparticle)

# Summary of collider results

Particles and antiparticles annihilate and/or often produced in pairs



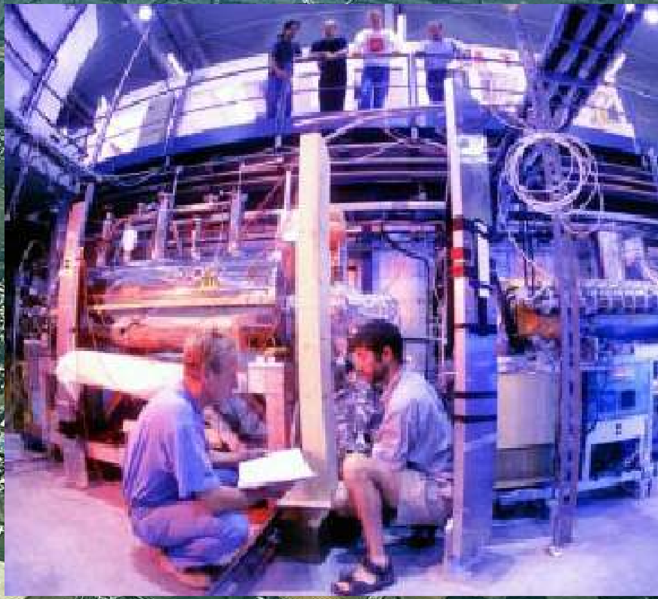

Matter and antimatter behave very similar, e.g. their interactions with photons are completely the same → by looking at your neighbour you cannot tell if he/she is made of matter or antimatter!


Only a very fews cases matter and antimatter do not behave exactly the same: CP violation in neutral Kaons
(a very tiny effect!)

Cronin & Fitch, Nobel 1980

# Summary of collider results

1995: Anti-hydrogen was produced at CERN consisting of an antiproton and a positron (since then a million pieces). So far it completely behaves as normal hydrogen.



ATHENA experiment; CE

Antimatter looks like matter

behaves very much like matter

is routinely produced in particle colliders

Is there antimatter in the cosmos?

# Direct search: AMS2 at ISS

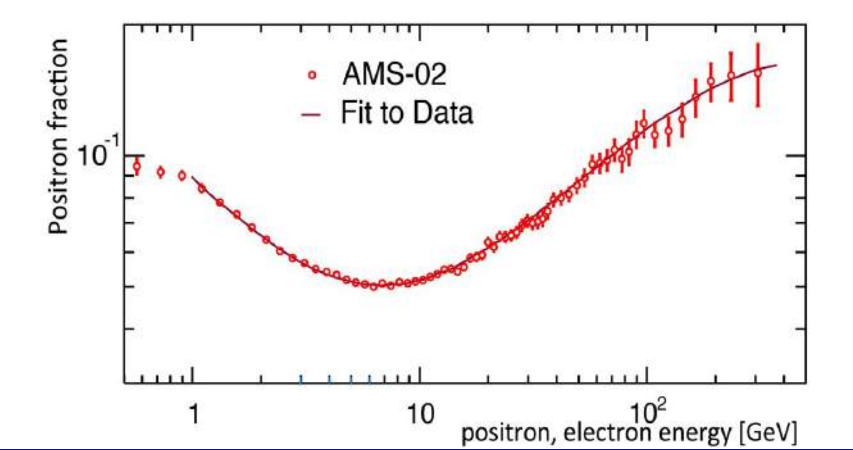
Launch: May 2011

Aim: look for antimatter close to earth

<u>Results:</u>

found lots of antiprotons and positrons

all most likely from annihilations somewhere in our galaxy




no anti-nuclei (eg. anti-helium)

→ there are no „anti-bodies“ close to earth

# Indirect search: what about outer space?

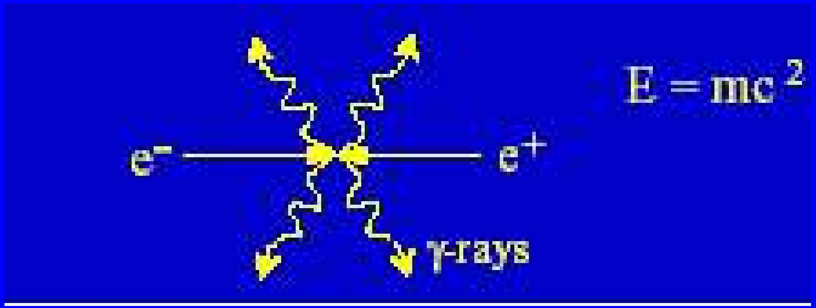
Nothing in the universe is completely isoloted.

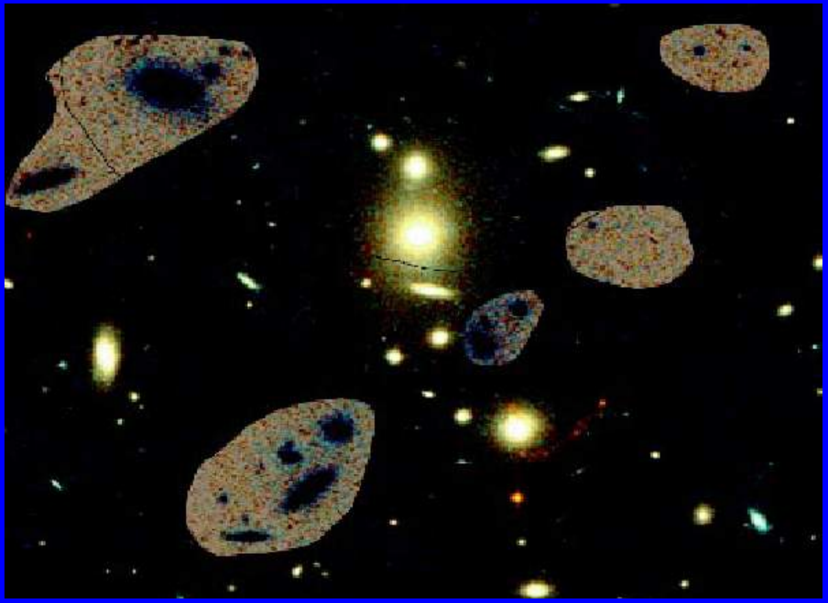
Even anti-galaxies or clusters would not be completely separated!

Look for **gamma rays** from **annihilation** at the boundaries of matter-antimatter domains.

**No signs of such a signal!!**

**→ there is practically no primordial antimatter in the present Universe!**



# What happend to the antimatter?

# Initial asymmetry... no, thanks

hot and dense beginning: the **big bang**

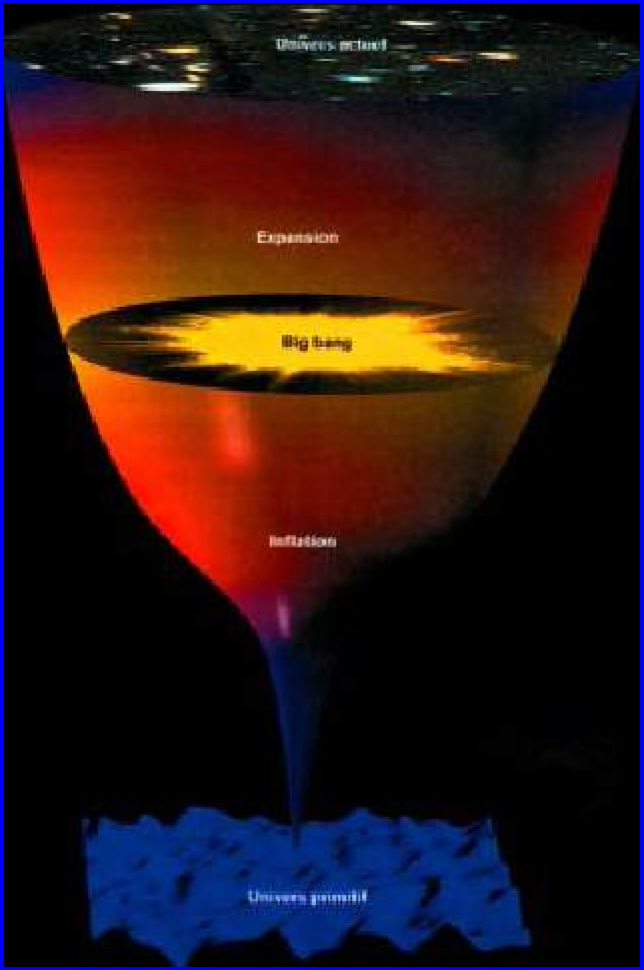
hot soup of quarks, leptons, photons, ...
**and their antiparticles!**

the universe expanded and cooled down

particles and antiparticles **annihilated**

**BUT when the possible particle-antiparticle annihilation ended, a small fraction of particles remained**

**→ there must have been an asymmetry between matter and antimatter!**




**A good way to quantify this asymmetry is** $\eta_B = \dfrac{\#baryons - \#antibaryons}{\#photons}$

# Initial asymmetry... no, thanks

Was the Universe born with a matter-antimatter asymmetry?

Better no, because:

- If possible, we like to find an explanation for the numbers we observe
- We have strong reasons to believe that there was an (inflationary) epoch producing a huge number of photons. So huge, that any initial asymmetry would have been diluted to almost zero.

Is it possible that the matter-antimatter asymmetry was generated during the history of the Universe?

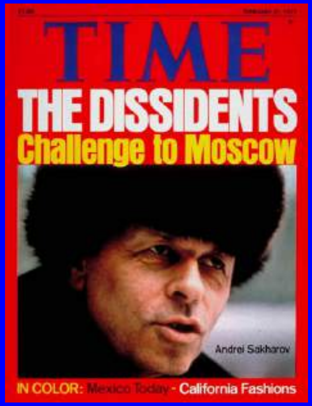

# Recipe for a baryon asymmetry

Under what conditions could a baryon asymmetry emerge („baryogenesis“)?

1) Baryon number must be violated (predicted at high T)

2) Particles and antiparticles cannot behave exactly the same („CP violation“, discovered in neutral kaons 1964)

3) The universe must be out of thermal equilibrium (there must be some arrow of time)




by Andrei Sakharov (1921-1989) in 1967; Soviet nuclear physicist; dissident (against the nuclear program); 1975 Nobel Peace Prize

# Phase Transition of the Higgs boson?

Was the universe boiling?

Was there a phase transition like water → vapor involving the Higgs?

Could this transition be responsible for the bayon asymmetry ?

How could we test the Higgs phase transition ?

How many phase transitions occurred to the Higgs boson?