CERN 60th Anniversary
Public conference programme
November 20 2014

Past, present future: LHC and future possibilities

Part 1: Open problems in particle physics after the Higgs discovery

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Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

The questions addressed by Particle physics are the same that guided the development of Natural Philosophy in the course of History

- How does the Universe work?
- Where does it come from?
- Where is it going?

- What are the ultimate components of matter?
- How do they "move"
- What "moves them"?

The most ambitious among all sciences!

Even the approach followed by ancient philosophers is similar to the one used by the modern physicist:

to indentify few fundamental principles, from which to derive the properties of all natural phenomena, both in the macrocosm (the sky, the Universe) and at the human scale

In common, the identification of two categories:

(a) The components of matter

(b) The forces that govern their behaviours

Example

Components:
air, water, fire, earth

Forces:
- air and fire pushed upwards
- earth and water pulled downwards

Judgement of correctness:
how come a tree falls in the water, but then gets pushed up and floats?

Reevaluation of the theory (Archimedes)
- **all** matter is pulled downwards, but with intensity proportional to its weight:

A body immersed in water receives a push upwards equal to the weight of the displaced water

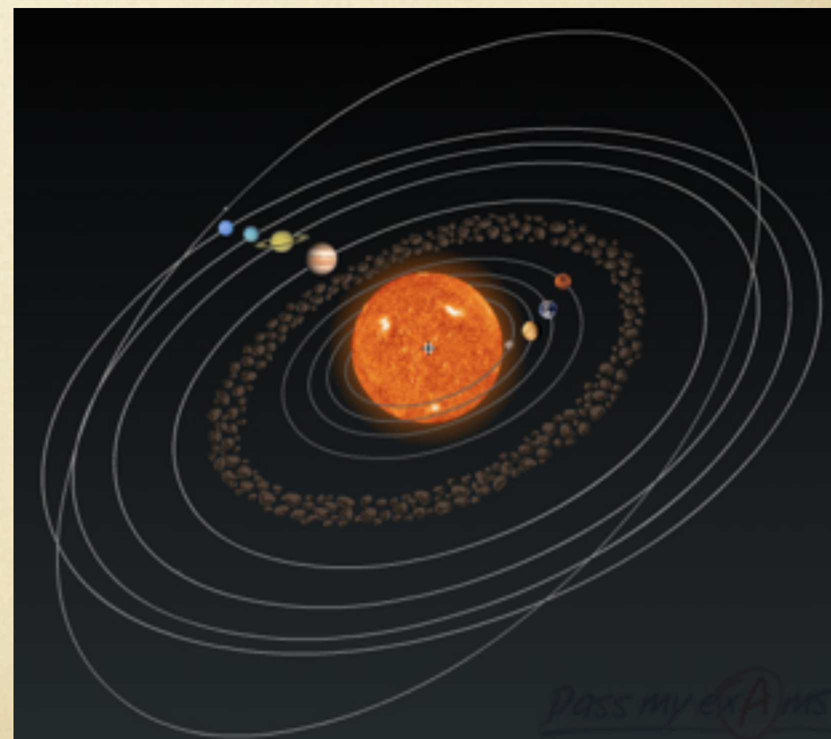
=> the first historical example of "unification of forces" ?

This theory is simpler, and better than the previous one, as it suddenly also explains new phenomena, like the wind: warm air is lighter than cold air, it goes up, and forces cold air to move in => the wind

Example: Unifying physics at the human and cosmic scales

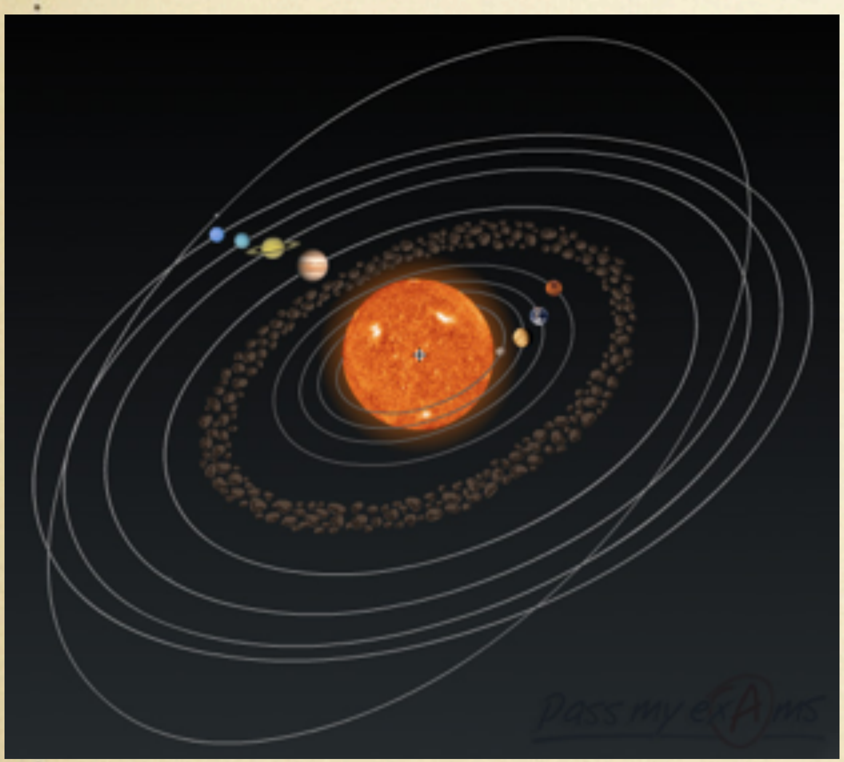
I.Newton

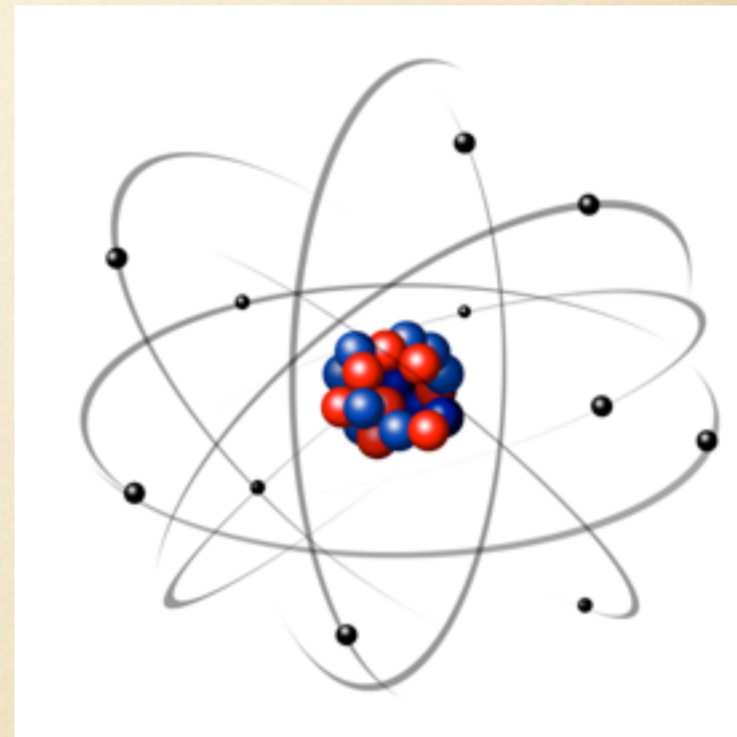
$$F = -G_N \frac{M\,m}{R^2}$$



Example: Unifying physics at the cosmic and microscopic scales

E. Rutherford





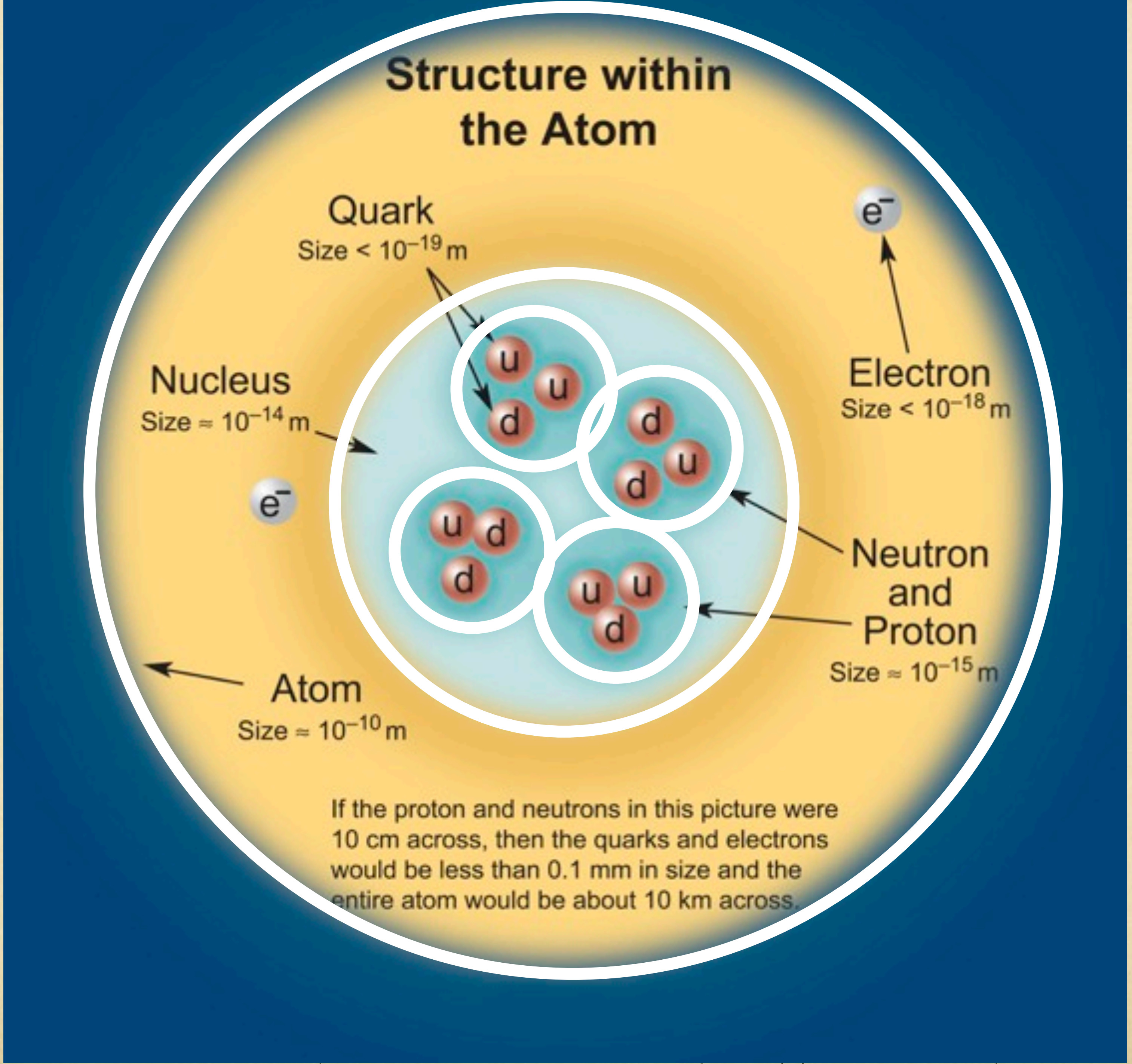
$$F = -G_N \frac{M\,m}{R^2}$$

I.Newton

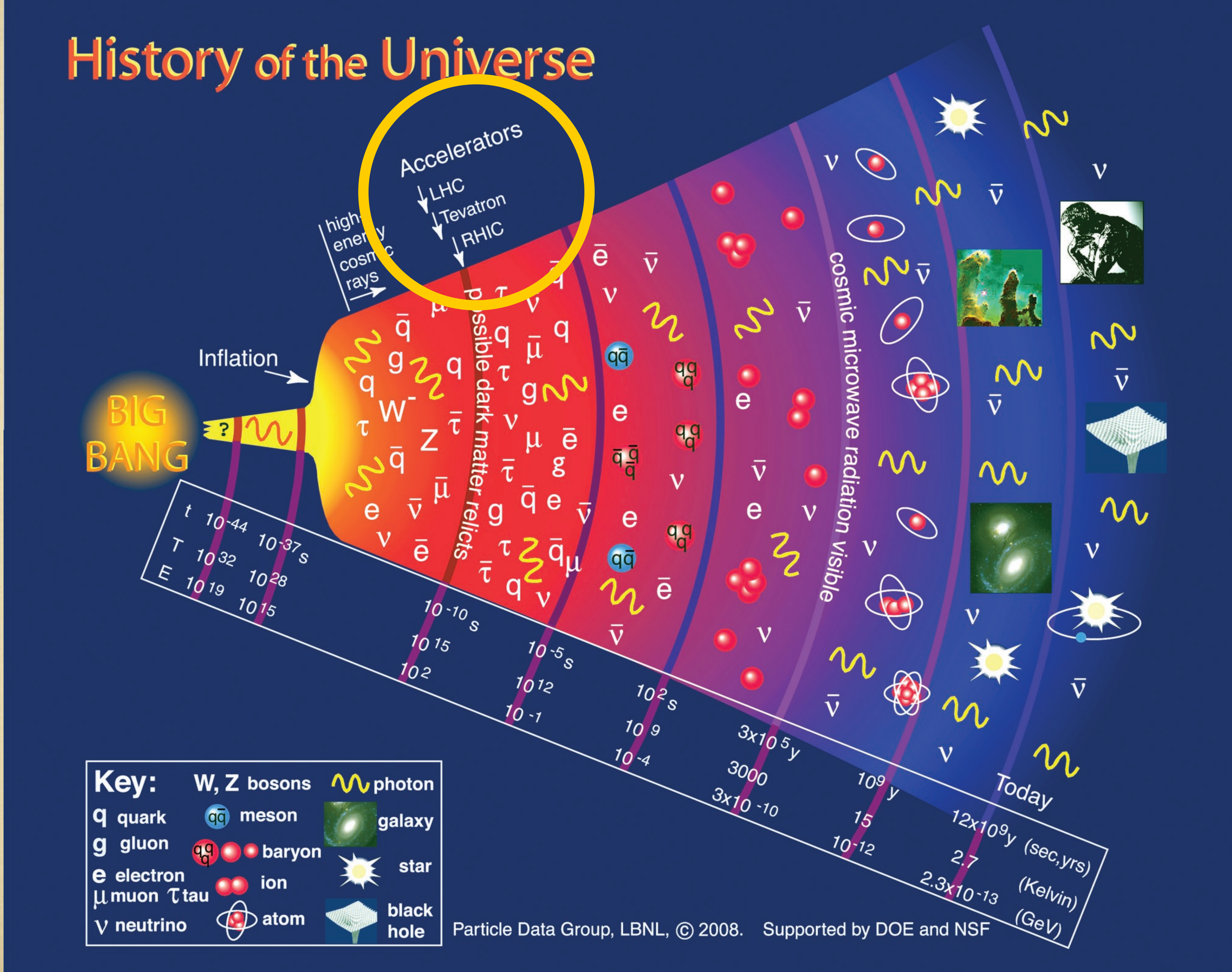
$$F = -\alpha \frac{Q\,q}{R^2}$$

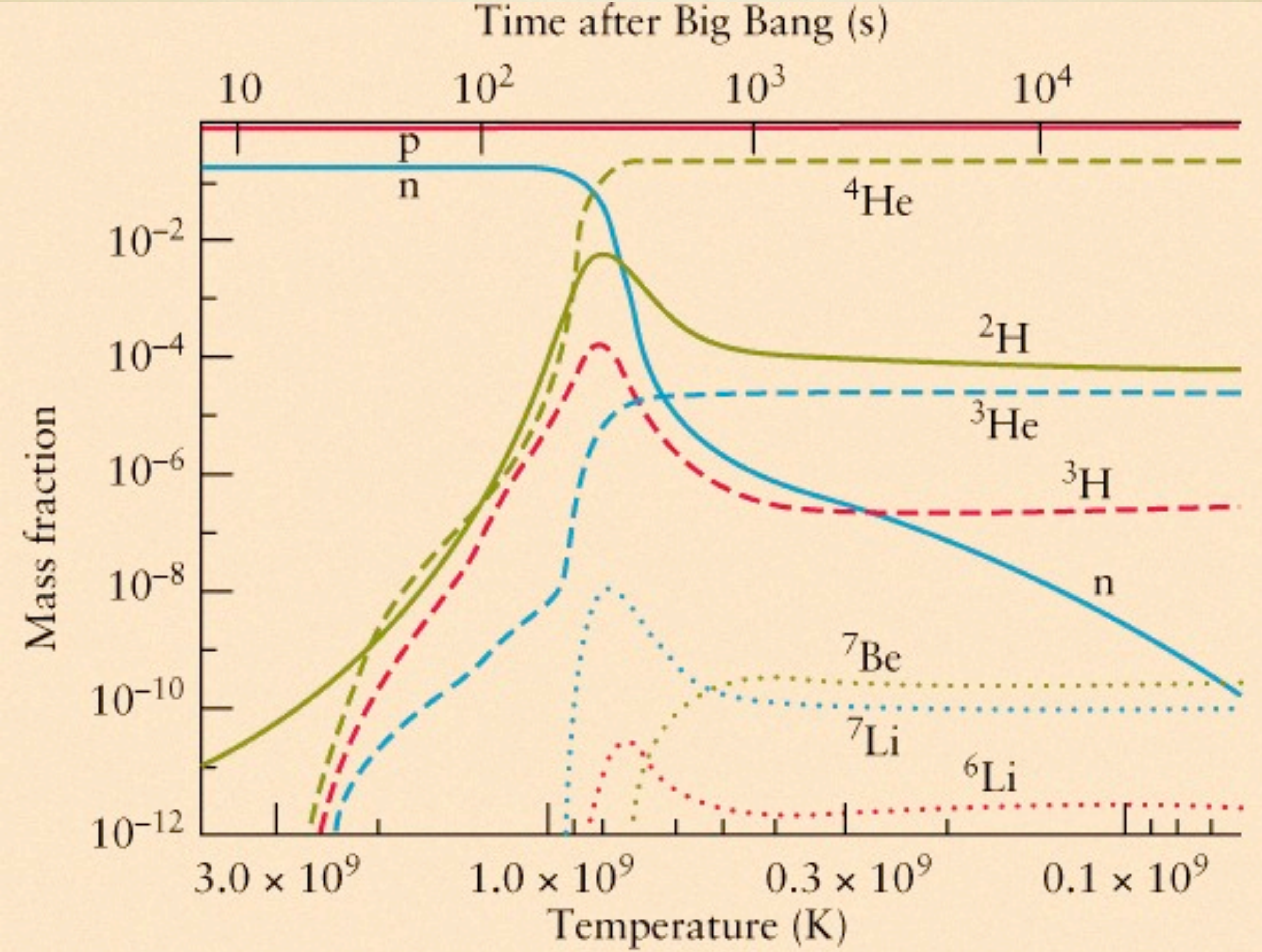
C-A de Coulomb

.... and from atomic to subnuclear ....



From: Contemporary Physics Education Project, http://www.cpepphysics.org/


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF



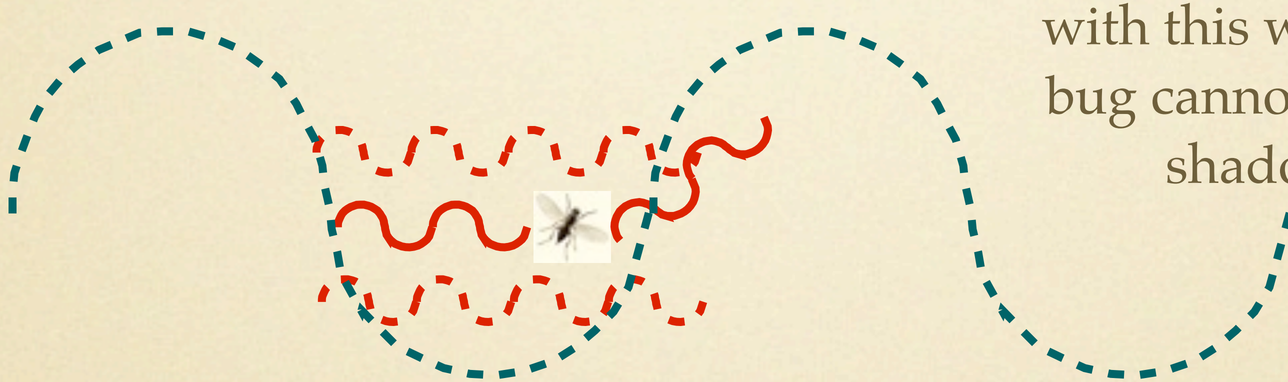
Time after Big Bang (s)
10
10^2
10^3
10^4
p
n
^{4}He
10^{-2}
^{2}H
10^{-4}
^{3}He
10^{-6}
^{3}H
10^{-8}
n
^{7}Be
10^{-10}
^{7}Li
^{6}Li
10^{-12}
Mass fraction
3.0×10^9
1.0×10^9
0.3×10^9
0.1×10^9
Temperature (K)


dark energy
73%
dark matter
23%
non-luminous atoms
(e.g. planets, dead
stars, dust, etc), ~4%
stars, neutrinos,
photons ~0.5%

The main task of CERN is to continue exploring the smallest scales, to unveil the phenomena that took place at the beginning of the history of the Universe, and which shaped its evolution until today

"Watching" the very small

- To resolve details at a scale L, we must use waves with a wavelength λ smaller than L



with this wave, the bug cannot leave a shadow!

E.g.: the radar at an airport operates with a wavelength λ~30cm. It cannot resolve the presence of a single flying bird!

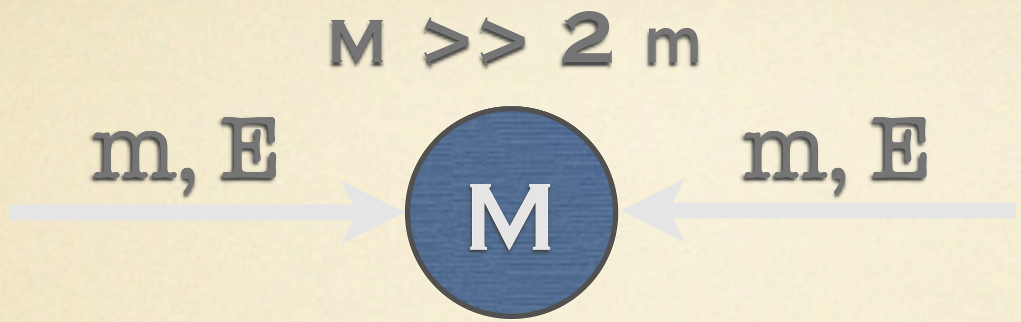
- The smaller L, the smaller the wavelength λ
- Since E ~ frequency and frequency ~ $1/\lambda \Rightarrow$
  - the smaller the object size L, the bigger the energy required to "see" it !

- This large energy, however, must be concentrated in a small volume, of a size comparable to λ

- a hammer hit carries much more energy than the light beam of a microscope, but we cannot see a microbe with it!

$\Rightarrow$ to study physics at the shortest distances, we need small probes, of the highest energies

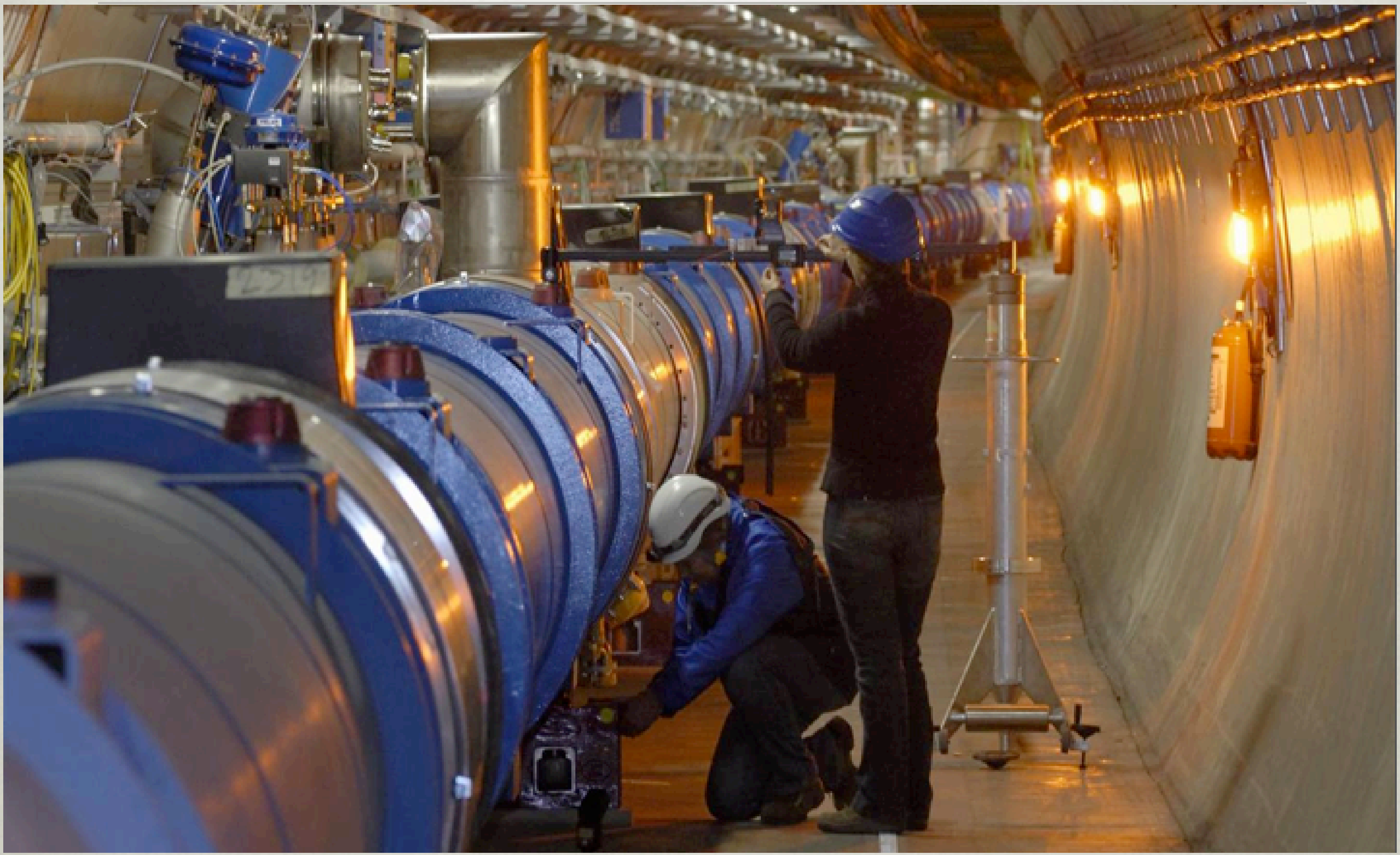
$$E = \frac{M\ C^2}{\sqrt{1 - \frac{V^2}{C^2}}}$$



$$\cancel{E} = M c^2$$

LARGE ENERGIES NOT ONLY ALLOW TO PROBE SHORT DISTANCES, BUT GIVE THE POSSIBILITY TO CREATE NEW, HEAVIER PARTICLES !!

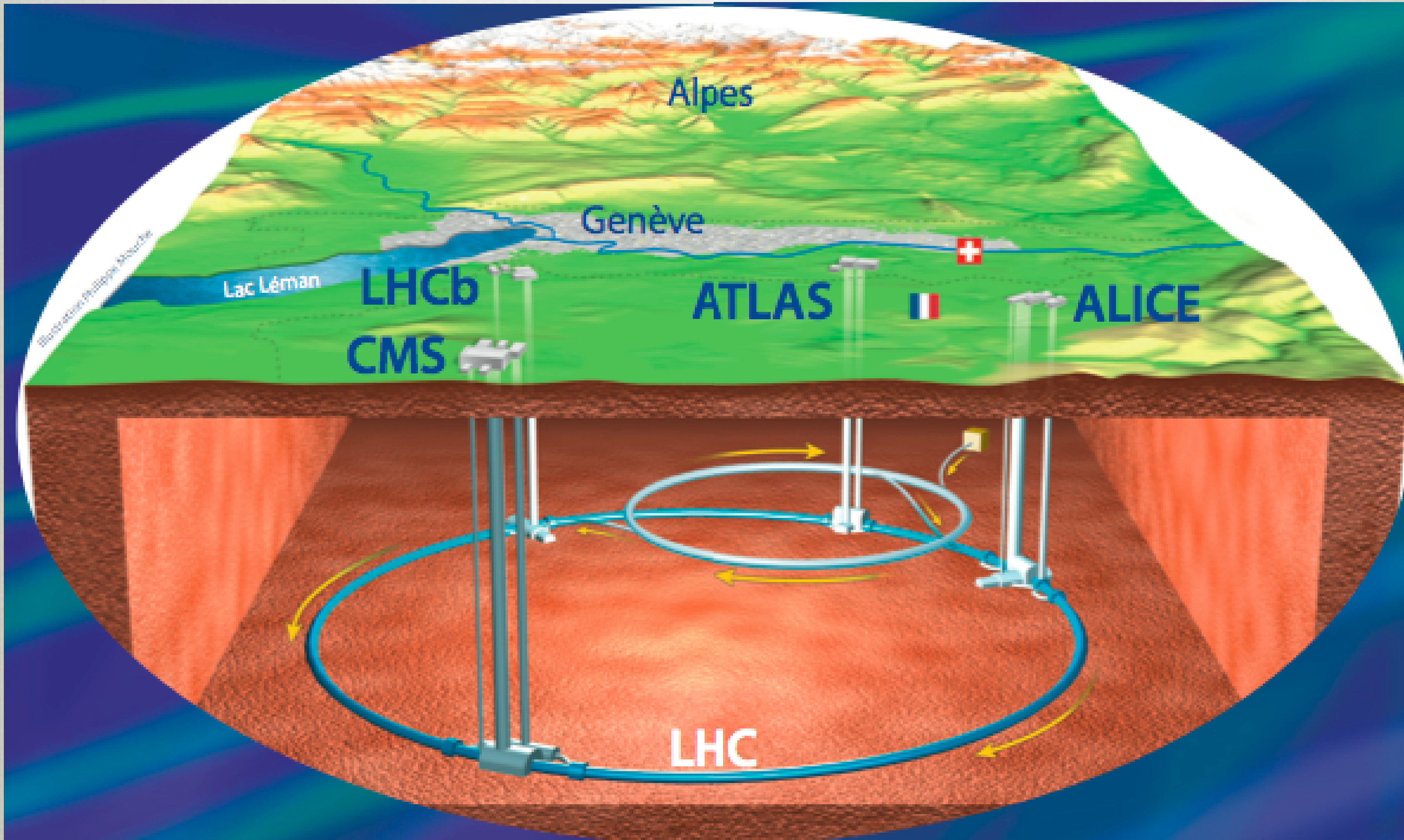
Enters the LHC



http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/blog-2007.htm


CERN
SUPER-PROTON SYNCHROTRON,
7KM (1976)
PROTON SYNCHROTRON
628M (1959)
LINAC
BOOSTER, 157M (1972)


CERN
LHC, 27 km
(1989 as LEP, 2008 as LHC)
super-proton synchrotron,
7km (1976)
proton synchrotron
628m (1959)
LINAC
booster, 157m (1972)

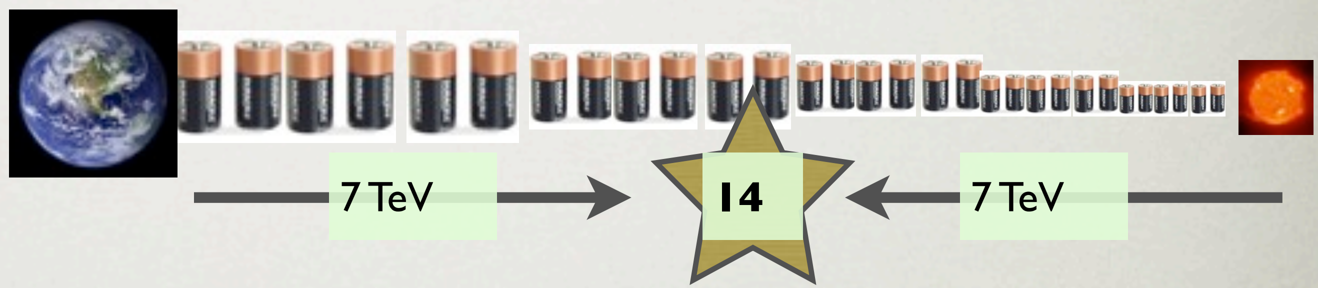

Alpes
Genève
Lac Léman
LHCb
CMS
ATLAS
ALICE
LHC

The LHC accelerator

- E_{beam} = 7000 GeV ~ 7500 $m_{proton}\, c^2$
  - $E=mc^2 / \sqrt{[1-v^2/c^2]}$ ⇨ v = 0.999 999 99 c

- E_{beam} = 7000 GeV ~ $7\text{x}10^{12}$ eV ~ 5 trillions 1.5V batteries

~ 100 M km of batteries, about d[Earth-Sun]



- N_{proton} ~ 10^{11}/bunch x 2800 bunches/beam x 2 beams ~ 10^{14}

- Energy stored ~ 350 MJ ~ 80 kg of TNT ~ TGV running full speed

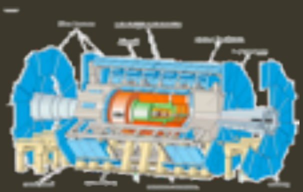
2808 PROTON BUNCHES

10,000 turns/sec

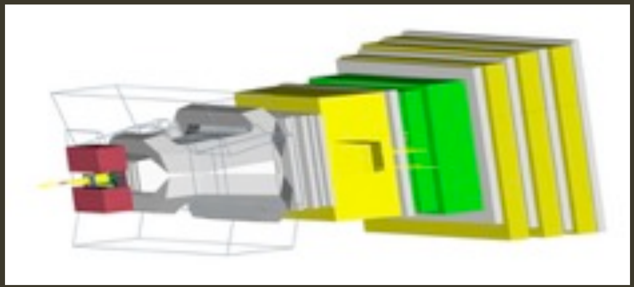
40Million bunch crossings per sec

CMS

ALICE

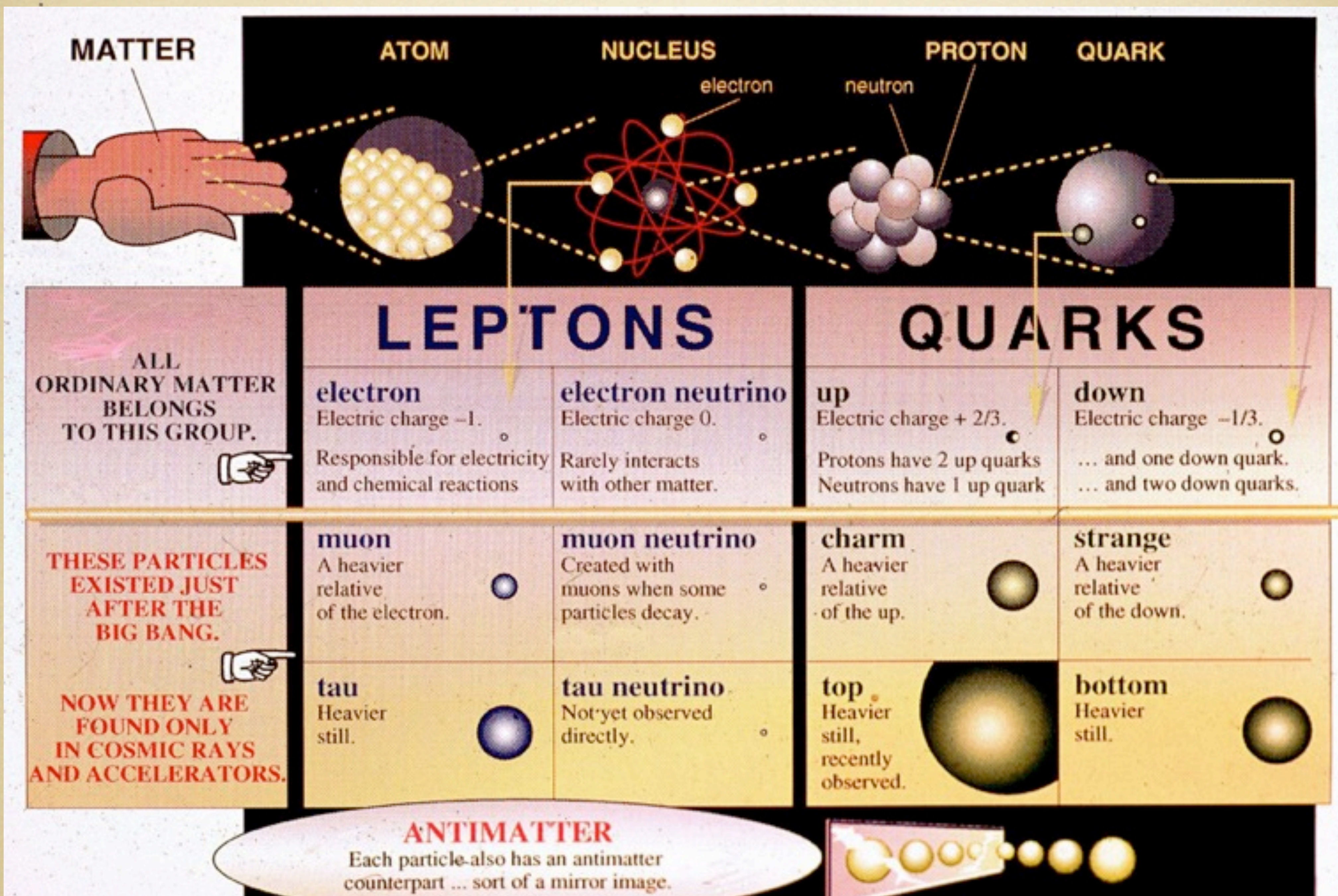


ATLAS



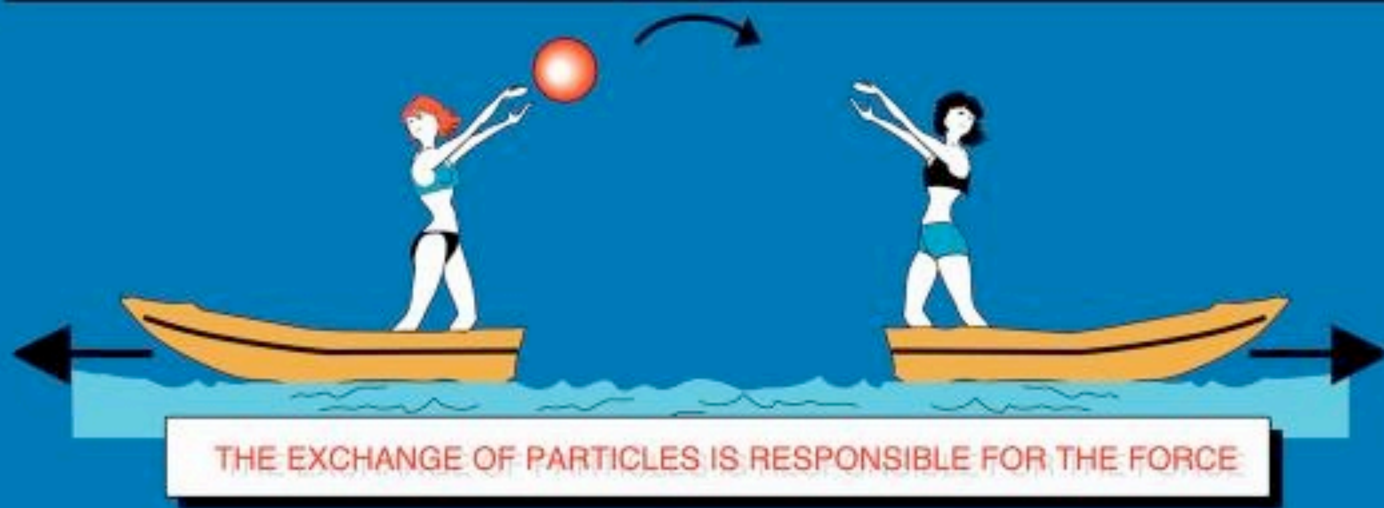
LHCb

The Standard Model

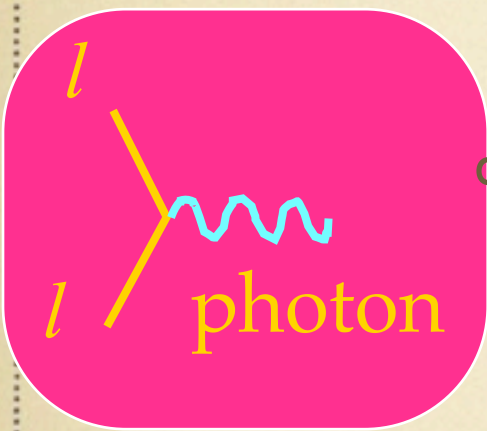

MATTER
ATOM
NUCLEUS
electron
neutron
PROTON
QUARK
LEPTONS
QUARKS
ALL ORDINARY MATTER BELONGS TO THIS GROUP.
electron
Electric charge –1.
Responsible for electricity and chemical reactions
electron neutrino
Electric charge 0.
Rarely interacts with other matter.
up
Electric charge + 2/3.
Protons have 2 up quarks
Neutrons have 1 up quark
down
Electric charge –1/3.
... and one down quark.
... and two down quarks.
THESE PARTICLES EXISTED JUST AFTER THE BIG BANG.
NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.
muon
A heavier relative of the electron.
muon neutrino
Created with muons when some particles decay.
charm
A heavier relative of the up.
strange
A heavier relative of the down.
tau
Heavier still.
tau neutrino
Not yet observed directly.
top
Heavier still, recently observed.
bottom
Heavier still.
ANTIMATTER
Each particle also has an antimatter counterpart ... sort of a mirror image.

The forces in Nature

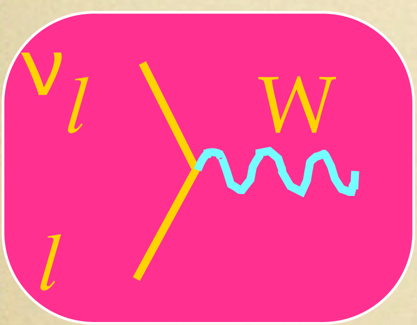
TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	~ 10^{-3}	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	~ 10^{-5}	BOSONS Z^{o}, W+, W- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	~ 10^{-38}	GRAVITONS (?)	HEAVENLY BODIES



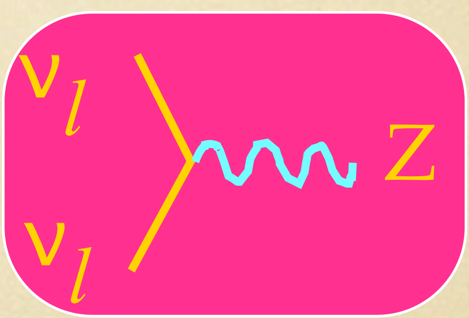
Lepton Interactions (l=e,μ,τ)



$\propto$ -e=electric charge

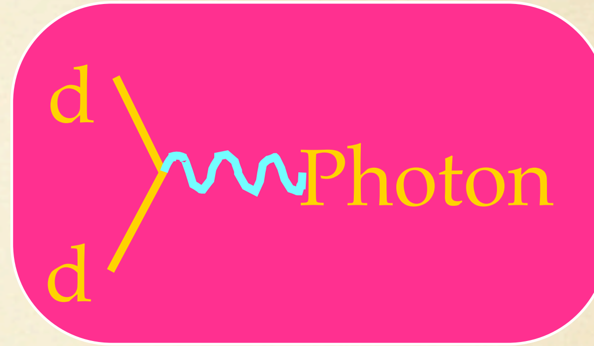


$\propto$ g_W=weak charge

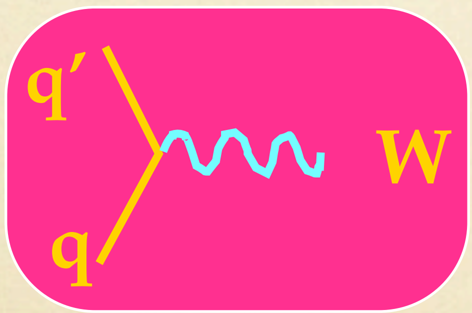


Quark Interactions

$\propto$ 2/3 e



$\propto$ -1/3 e



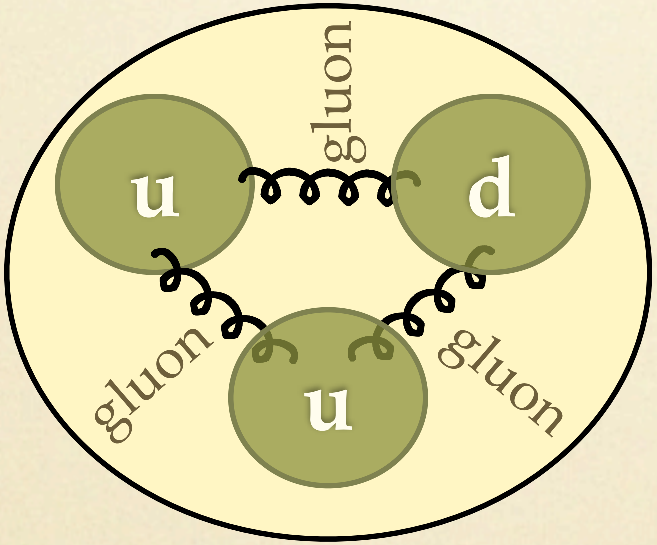
$\propto g_W$

$\propto g_s$ =strong coupling

From these fundamental building blocks (elementary particles and interactions), one gets all matter that we are made of, that surrounds us, and that forms all structures observed in the universe: planets, stars, galaxies

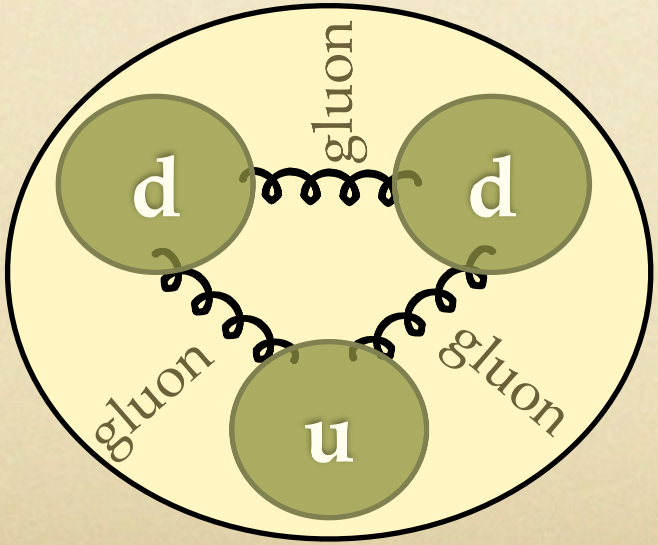
Example

Proton



Q = 2/3 e +2/3 e –1/3 e
= e

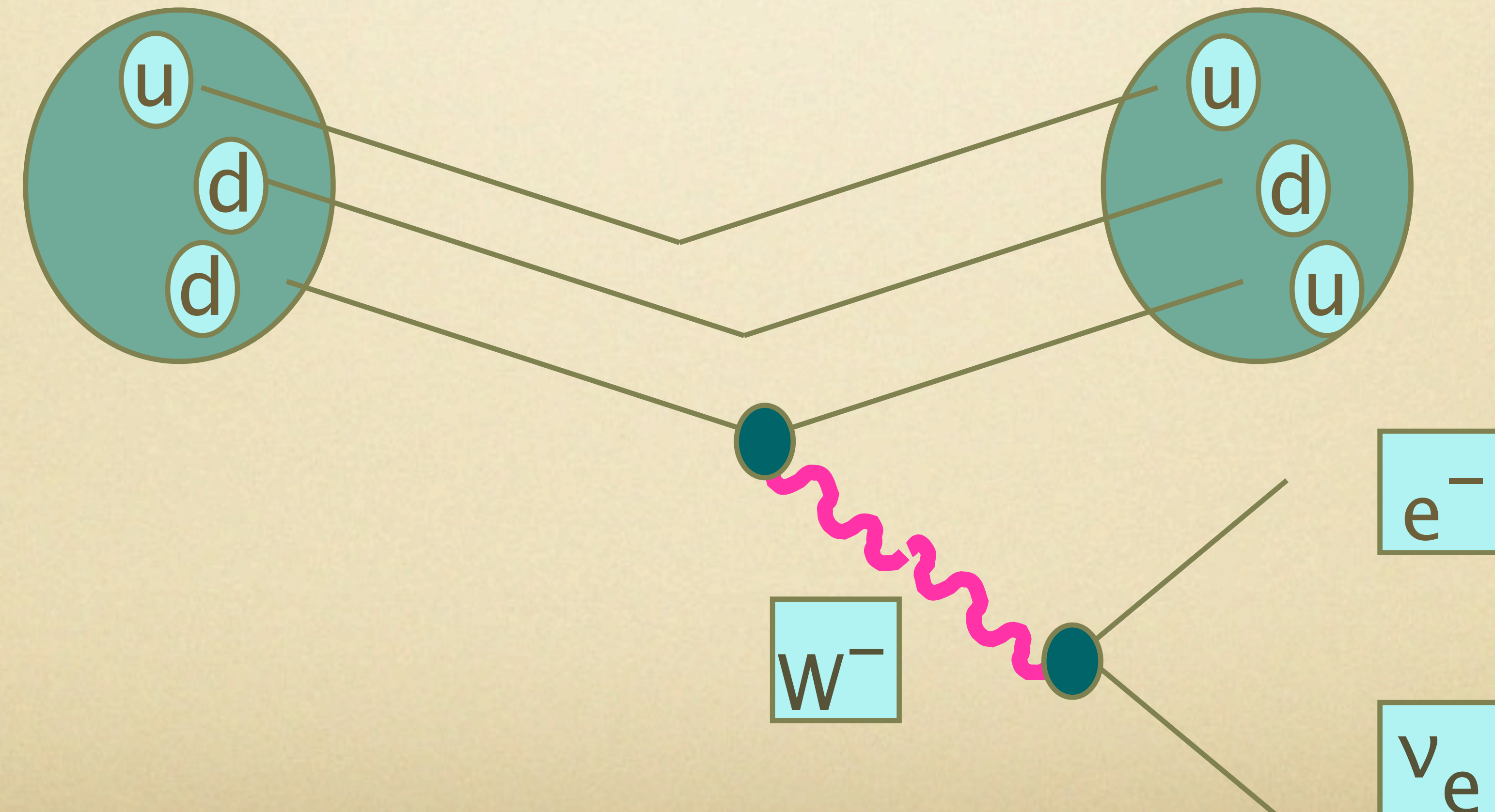
Neutron



Q = 2/3 e –1/3 e –1/3 e
= 0

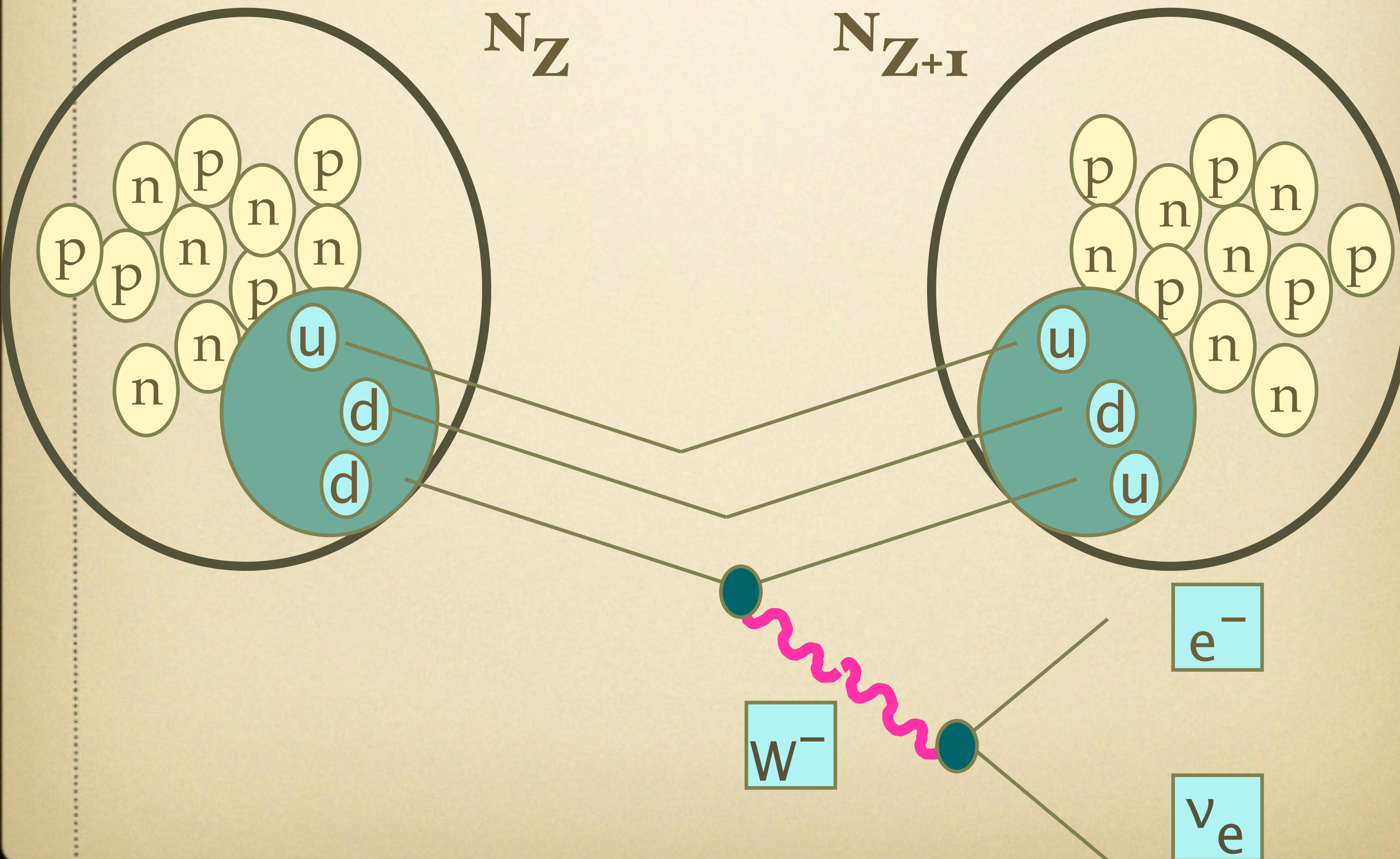
Example: neutron decay

n → p electron neutrino



Example: radioactivity

$N_Z \rightarrow N_{Z+1}\, e\, \nu$



Transformations like the previous one, in which protons and neutrons turn into each other with emission of electrons and neutrinos, gave rise at the beginning of the Universe to the generation of all light elements (hydrogen, deuterium, helium,litium, etc)

$$\text{E.g.: } 4\,p \rightarrow He + 2\,e^{+} + 2\,\nu + 1.6 \times 10^{-13}\,J$$

$$4 \times 10^{-17}\ \text{Kcalories}$$

They are the driving mechanism for energy creation in the stars, transforming the lighter elements into heavier ones. In the biggest stars, this leads to the creation of heavy nuclei like **oxygen, silicon, ..., iron**. At the end of their lives, the gravitational pressure leads to a gigantic final collapse, followed by an explosion that scatters all these elements through space where, meeting gas nebulae ready to form new stars, they give rise to planetary systems like ours.

The Higgs boson

The vacuum, and the Higgs field

We call vacuum the state of any volume of the Universe if we were to take away from it all matter and interactions from nearby matter.

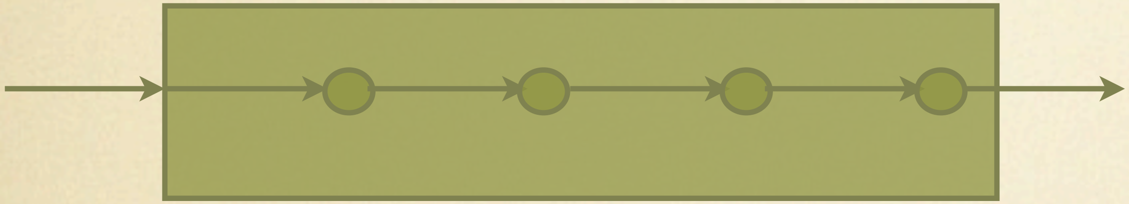
The Standard Model predicts that the vacuum is occupied by a constant density field of the Higgs boson, which we cannot “take away”.

This permeates the Universe like an ether, everywhere and permanently, since about 10^{-10} seconds after the Big Bang

Interacting with this field, particles acquire their mass

The Higgs and particles' masses

Light propagating in a medium is slowed down by its continuos interaction with the medium itself



The time it takes to move across the medium is longer than if light were propagating in the vacuum,

$\Rightarrow c_{medium} < c_{vaccum}$

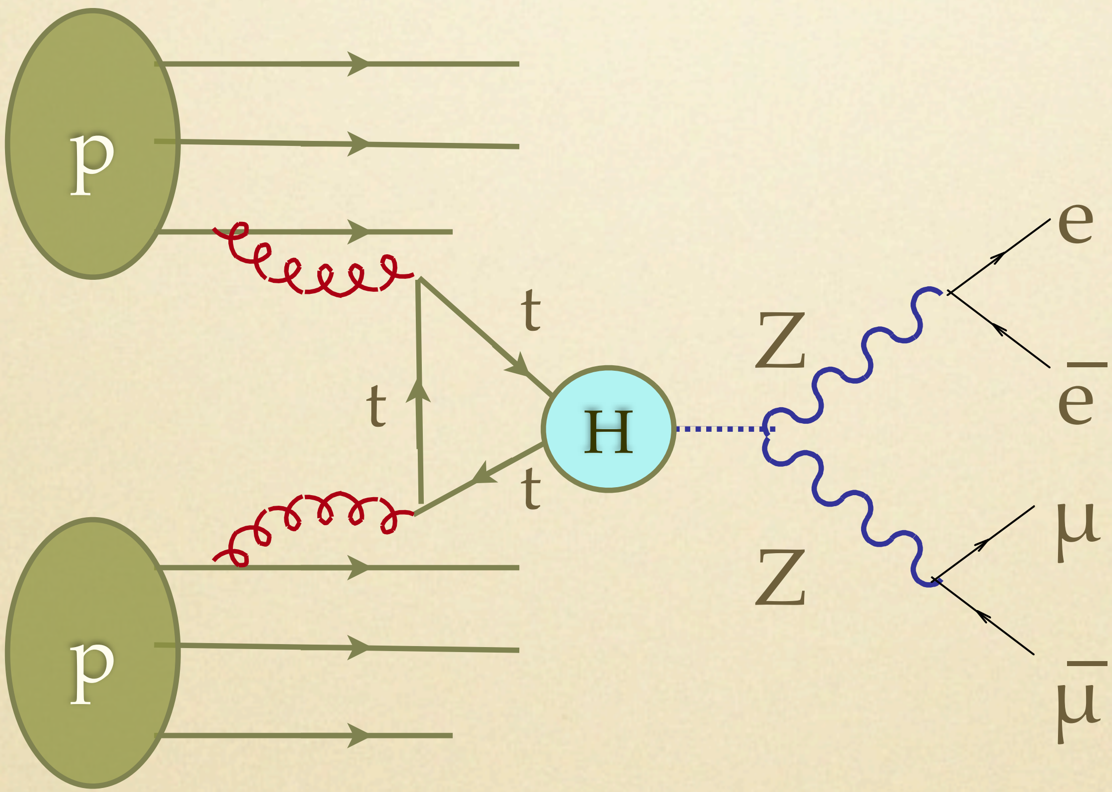
Think of the Higgs field as being a continuum medium embedding the whole Universe. Particles interacting with it will undergo a similar "slow-down" phenomenon. Rather than "slowing down", however, the interaction with the Higgs medium gives them "inertia" => mass

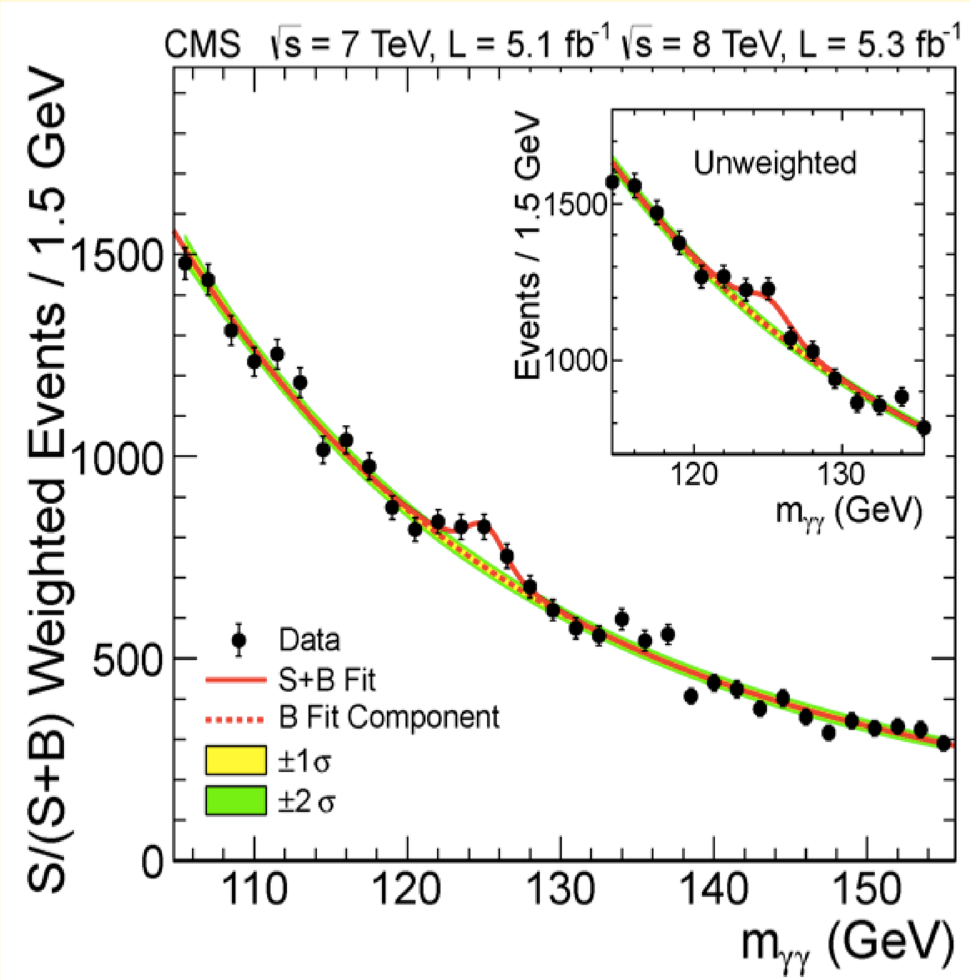
Detecting the Higgs boson

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”. These waves manifest themselves as particles , the so-called Higgs bosons

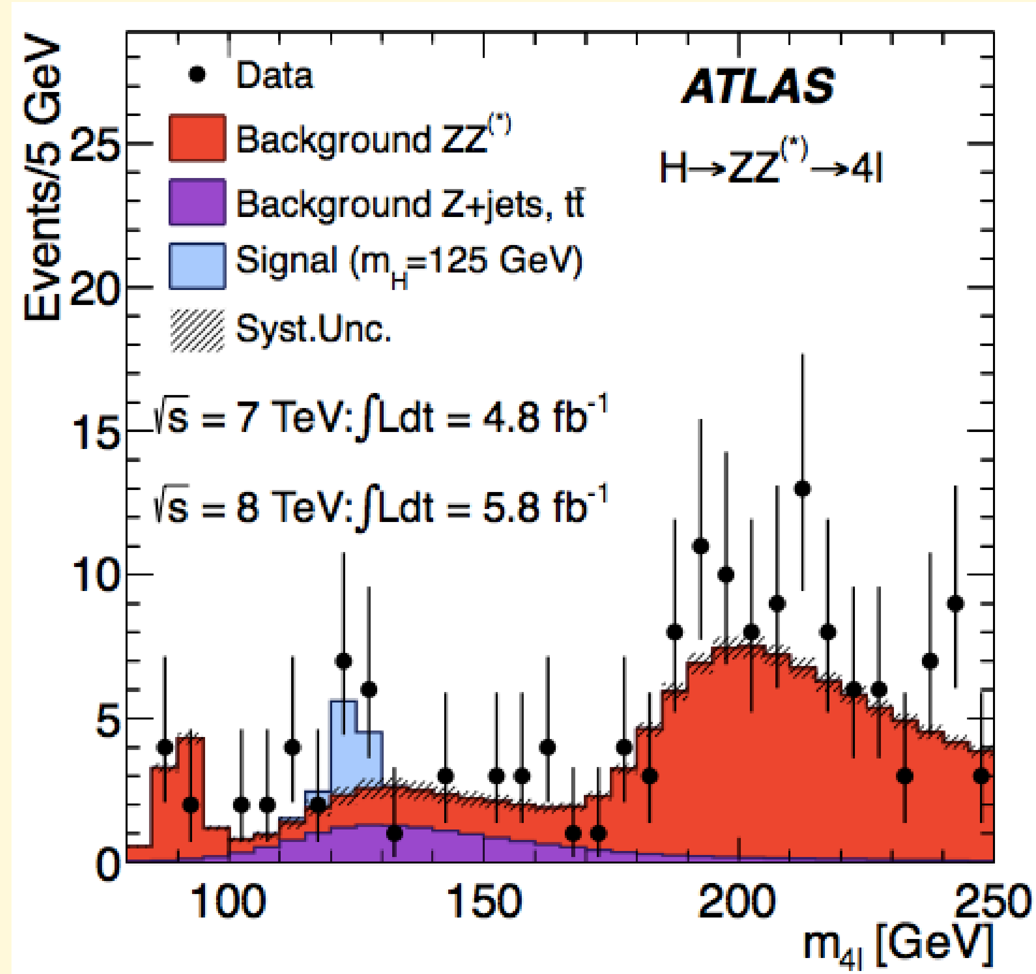
What is required is that the energy available be larger than the Higgs mass $\Rightarrow$ LHC !!!

Higgs production at the LHC





H→2 photons

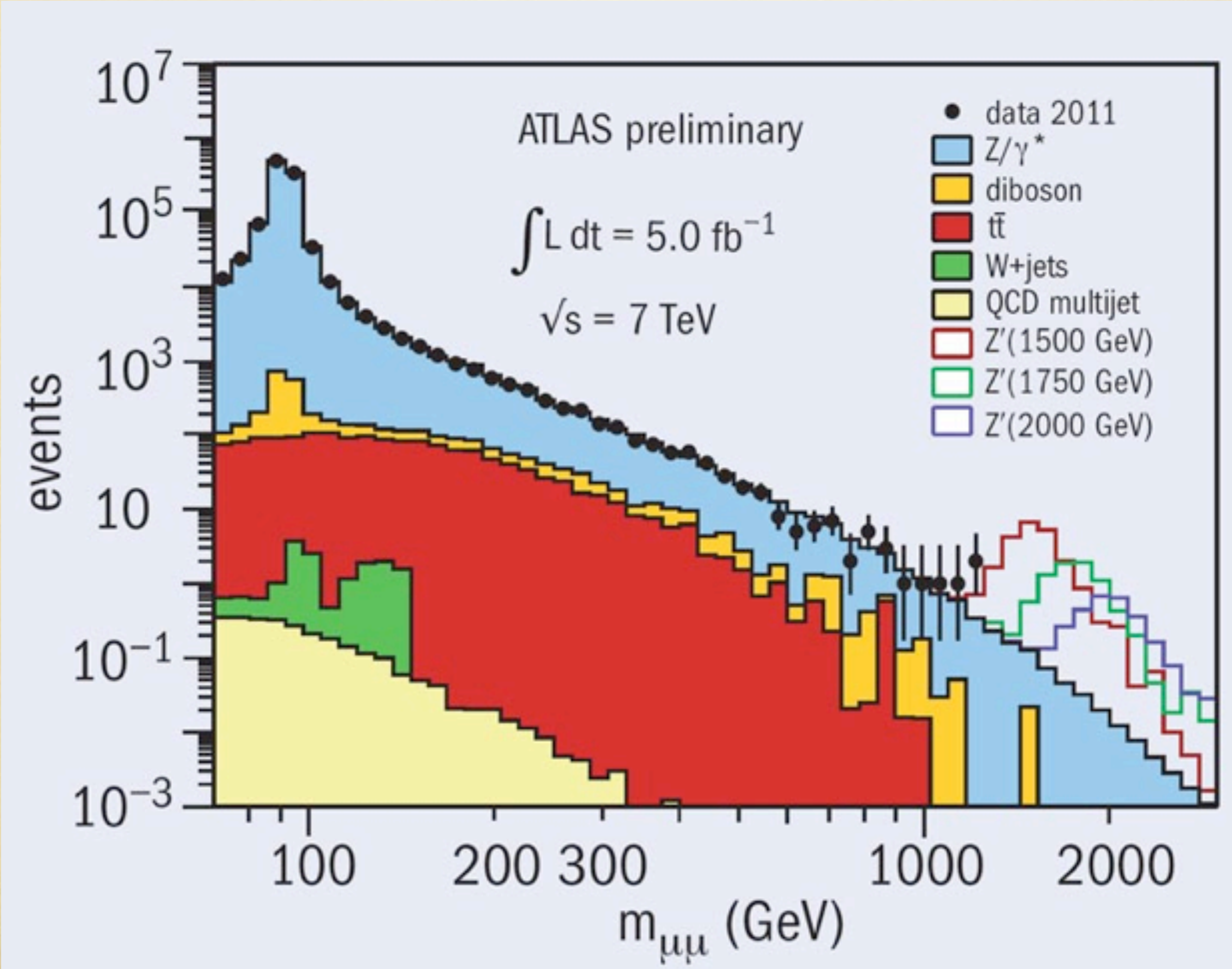


H→ZZ*→4 leptons

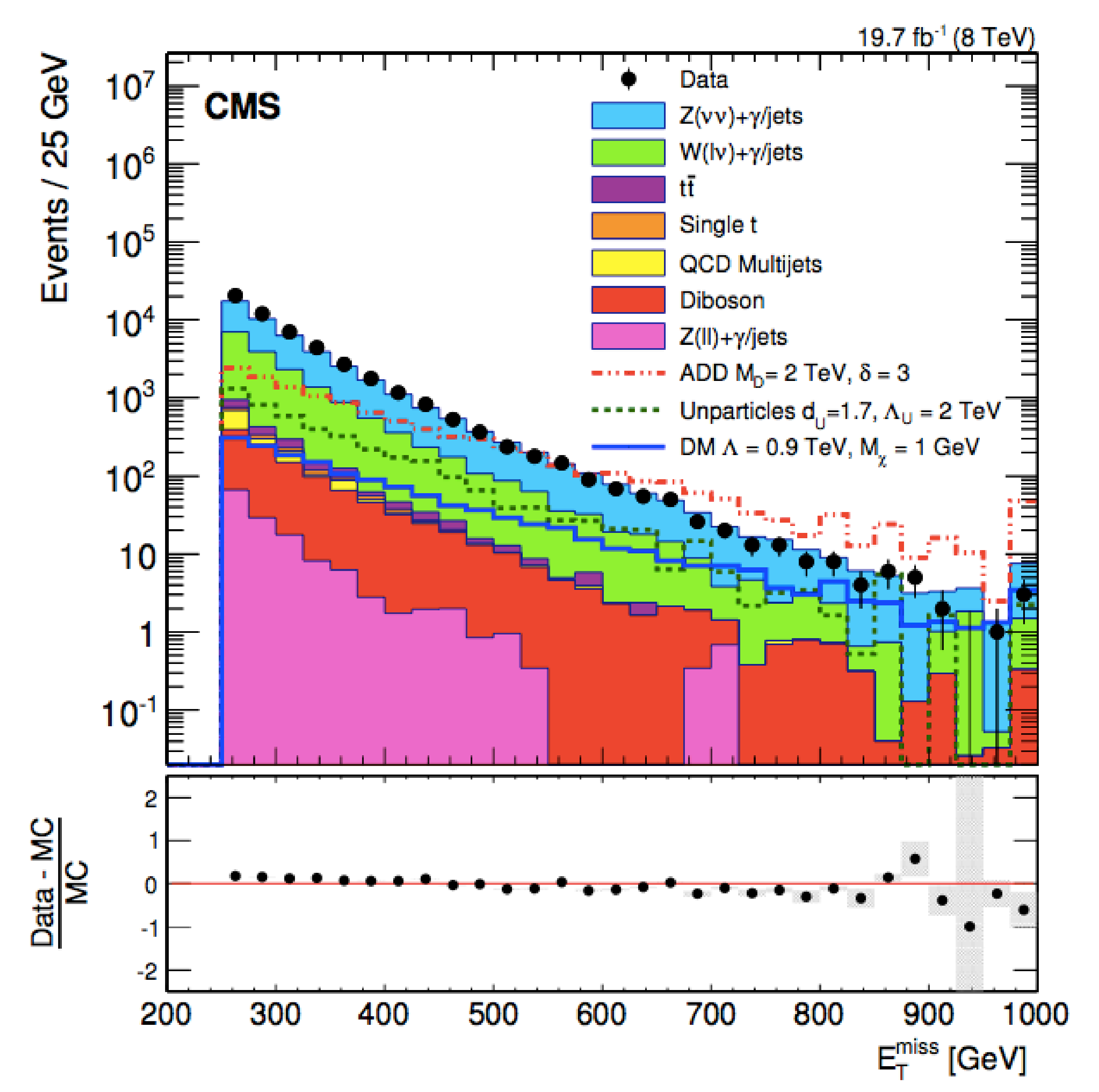
The goals of the LHC

- To firmly establish the **“what”**:
  - discover the crucial missing element of the Standard Model, namely the **Higgs boson => done !**
  - Are there new fundamental interactions, too weak to have been observed so far ?
  - Are there new generations of quarks or leptons ?
  - Are quarks & leptons elementary or do they have a substructure?
  - What is the particle responsible for the **Dark Matter** in the Universe ?

Searching for new forces ....



Searching for DM or extra dimensions ....



The goals of the LHC

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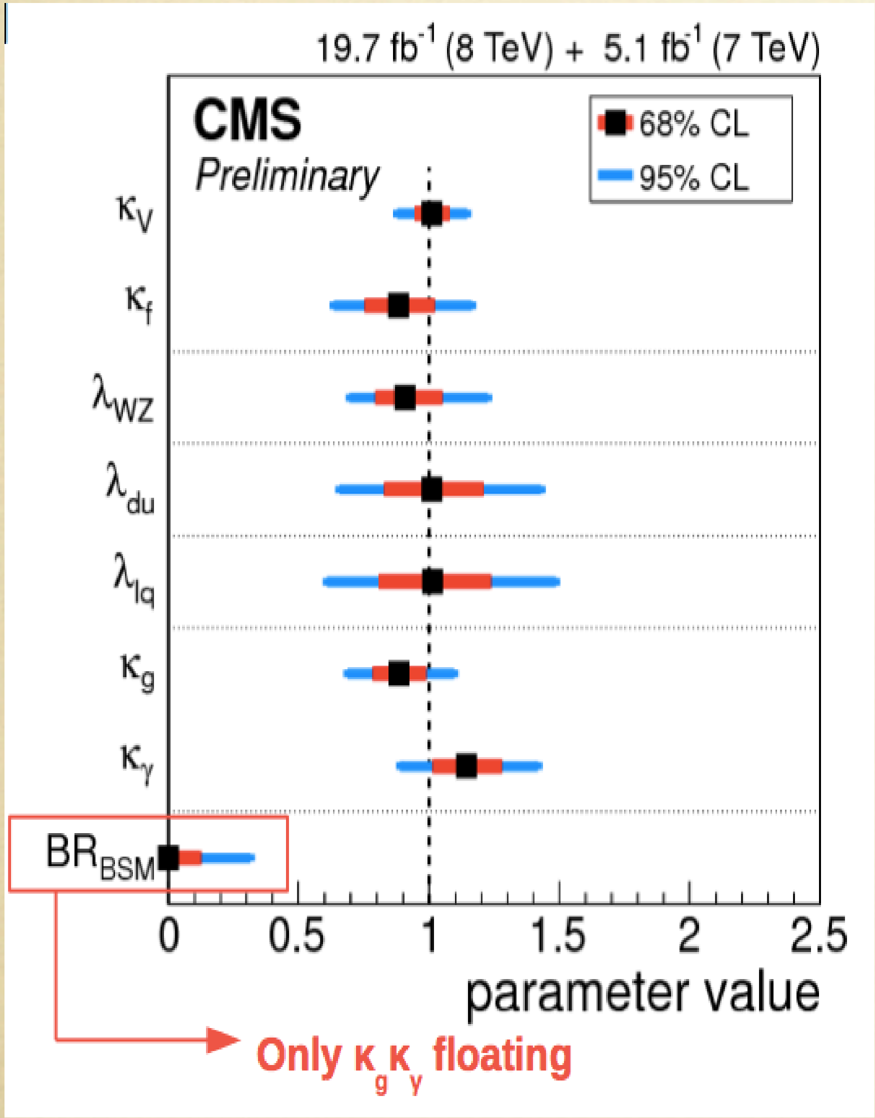
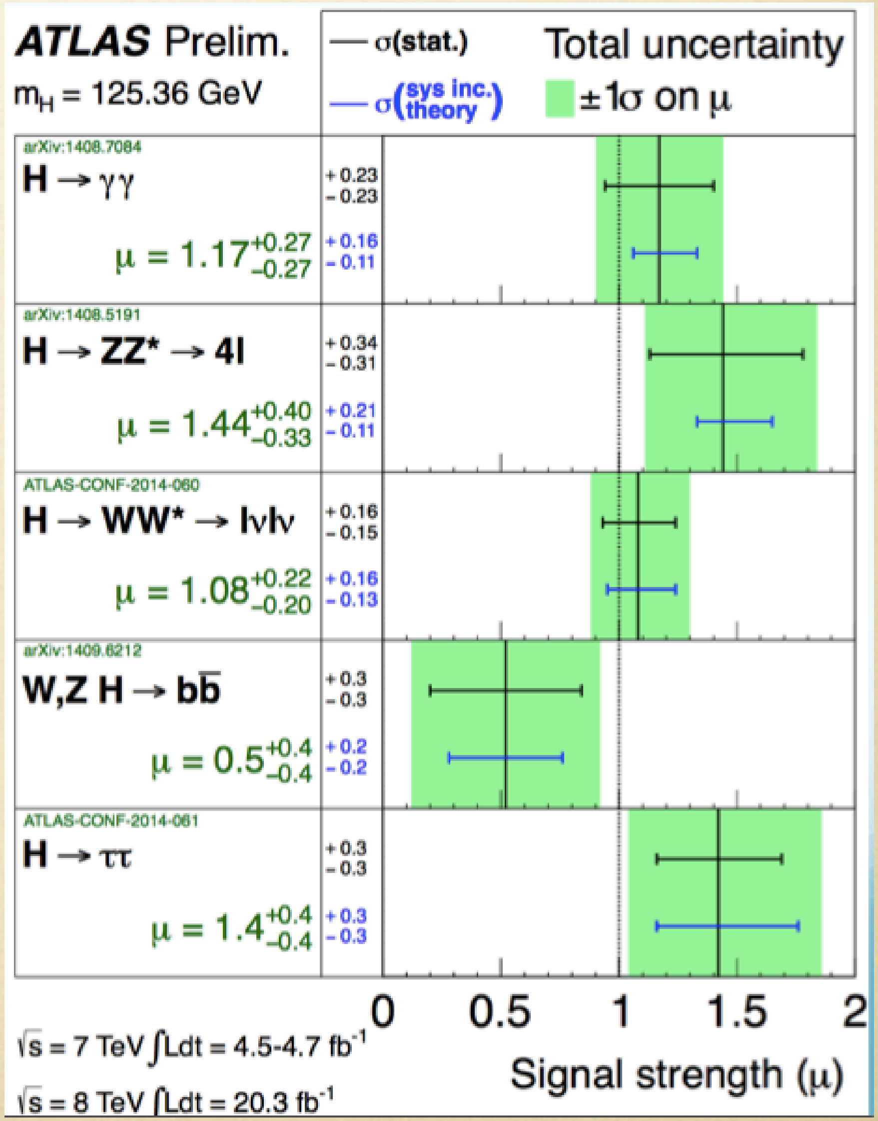
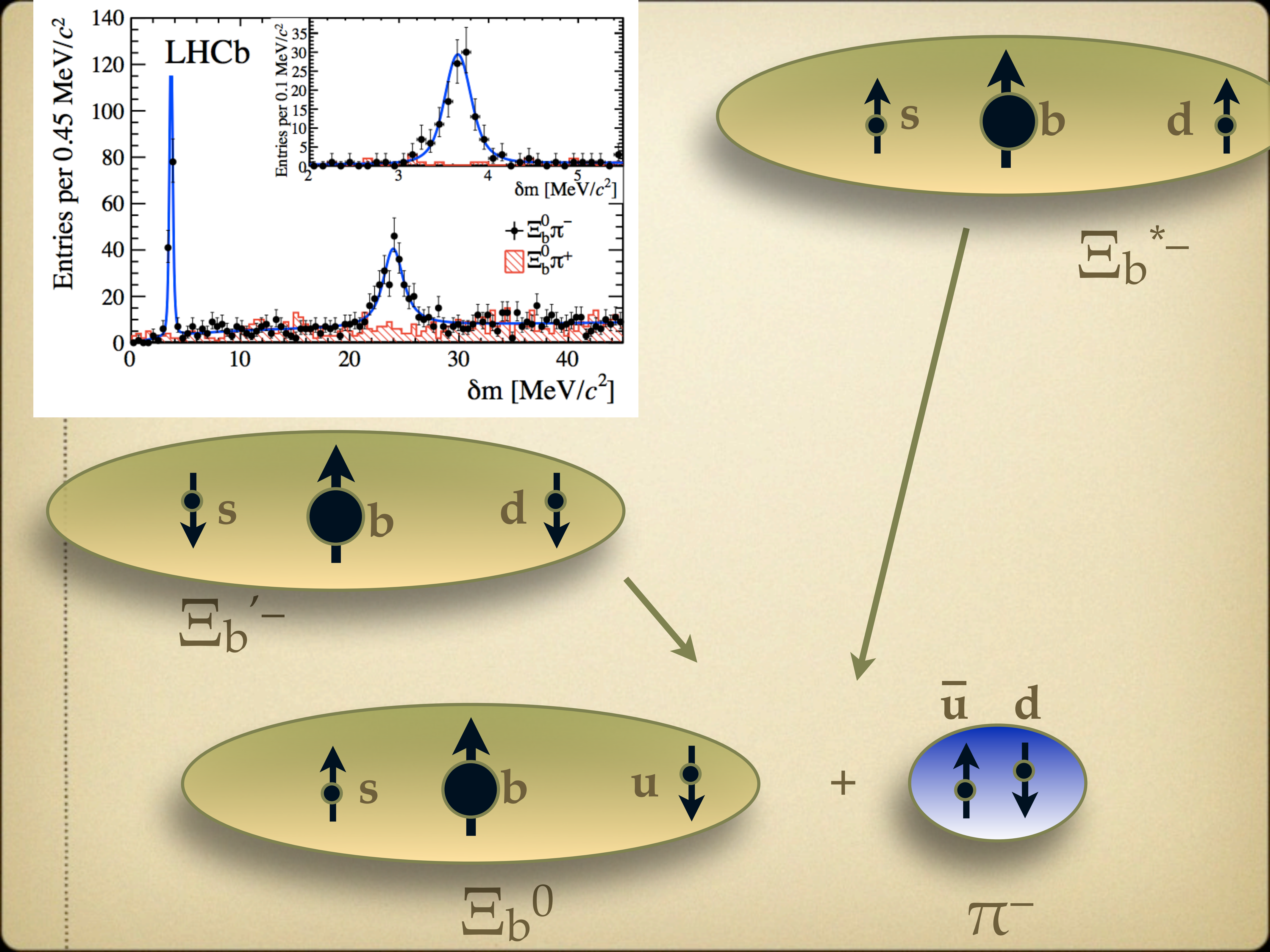
  - What is the particle responsible for the **Dark Matter** in the Universe ?

- To firmly establish the **"how"**:
  - "how" particles acquire a mass: is the Higgs mechanism of the Standard Model correct? => continue study of Higgs properties
  - "how" does the strong force work
  - "how" matter behaves under the Big Bang conditions of high density and temperature => continue study of heavy ion collisions

Probing Higgs properties ...

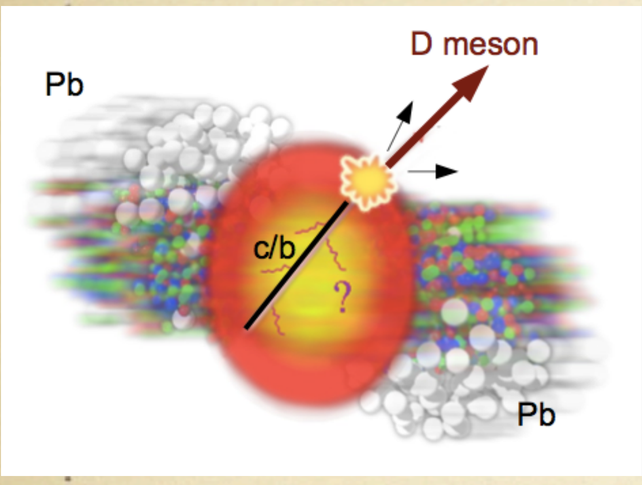


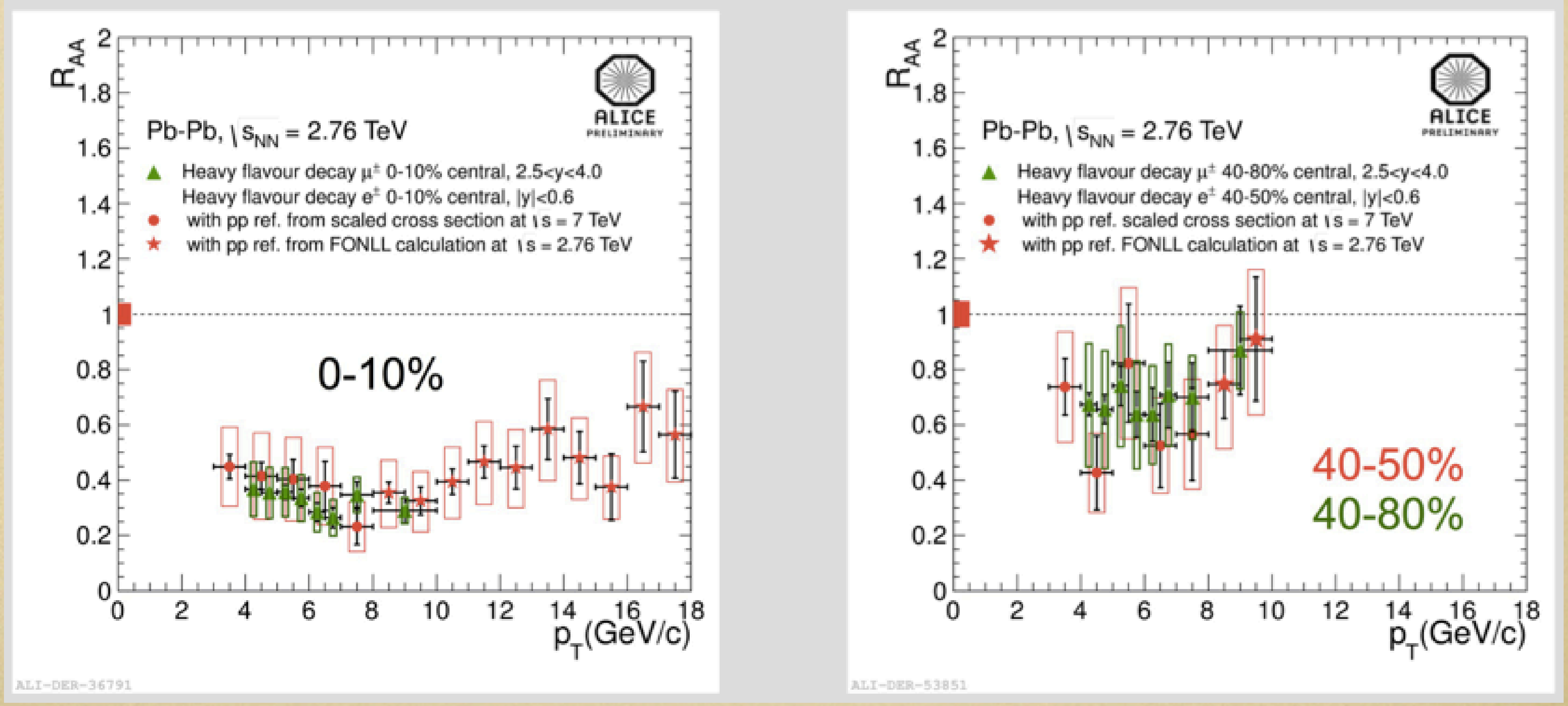




LHCb
Entries per 0.45 MeV/c^2
δm [MeV/c^2]
Entries per 0.1 MeV/c^2
δm [MeV/c^2]
$\Xi_b^0\pi^-$
$\Xi_b^0\pi^+$
s
b
d
Ξ_b^{*-}
s
b
d
$\Xi_b'^-$
s
b
u
Ξ_b^0
+
$\bar{u}$
d
π^-

Studying progagation through the quark-gluon plasma ...





So far, no deviation from the predictions of the SM has been found!

- Good news !
    - The Standard Model is confirmed !!
- Bad news !
    - If we don't see deviations from the SM, how do we move forward, towards answering other big questions ?

Big questions still open after the first 3 yrs of LHC

- **What is the real source of the Higgs field that permeates the Universe?**

- **What** are the particles forming dark matter?

- **How** was the matter-antimatter asymmetry of the Universe generated?

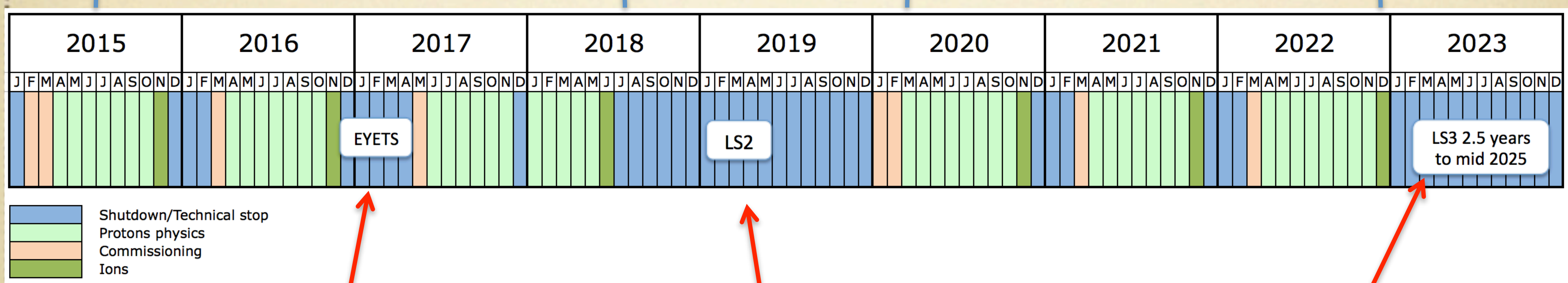
- **Why are there 3 families of quarks and leptons,** so similar but also so different from each other ? Why are neutrinos so different from everything else ?

- .....

The LHC, next steps

Run 2: 13 to 14 TeV c.m. with peak luminosity of ~1.7×10^{34} cm^{-2} s^{-1}

Run 3: 14 TeV c.m. with peak luminosity of ~2×10^{34} cm^{-2} s^{-1}



EYETS ~5 months
Extended year end technical stop (CMS)

LS2: 18 months
Connection of LINAC4
LHC Injectors Upgrade

LS3: 30 months
High Luminosity LHC

to be followed by 10 more years, 2025-2035, to collect >100 times more data than currently available !!