Mapping the Secrets of the Universe
With the Large Hadron Collider at CERN

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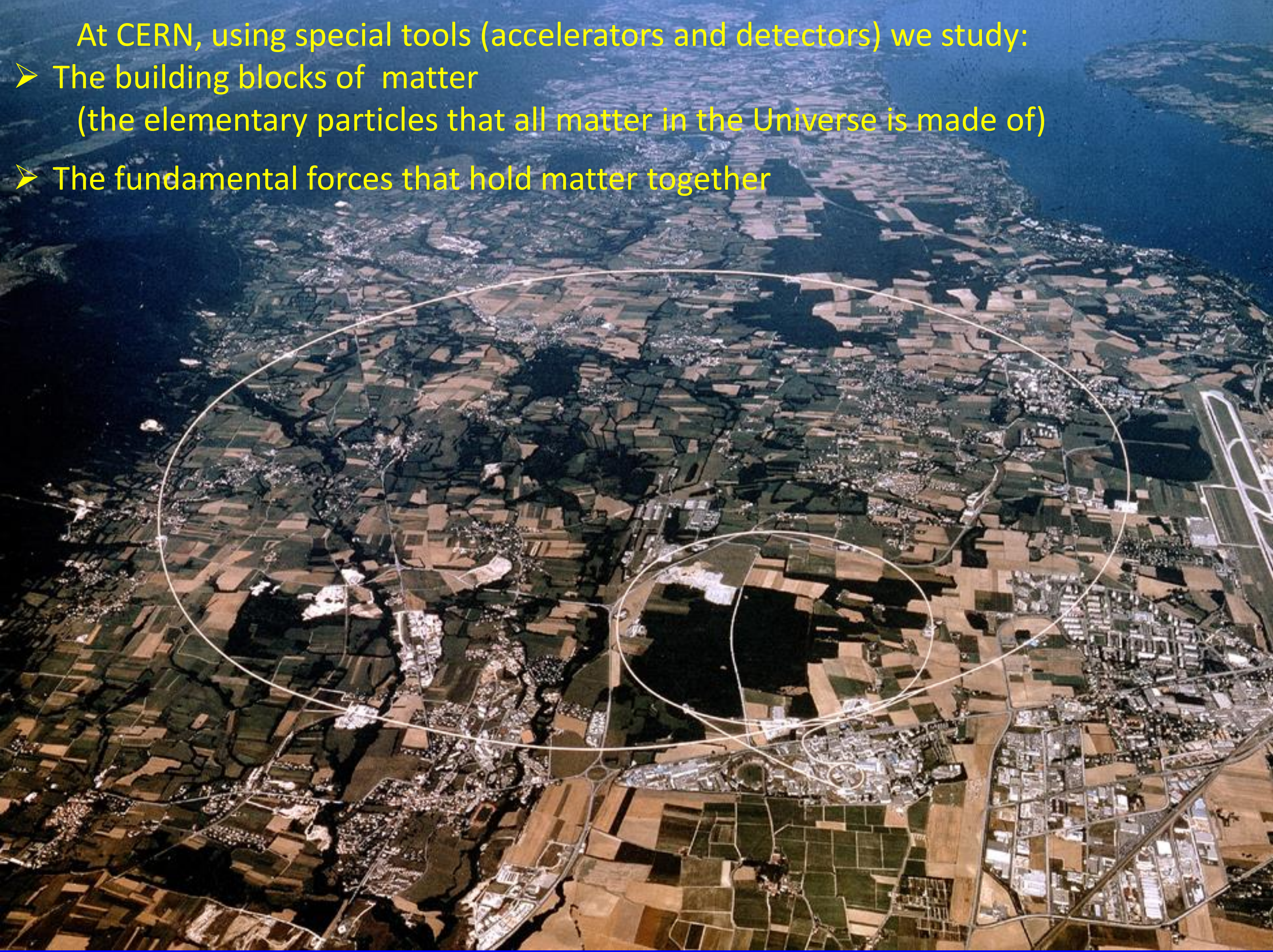
CERN : European Organization for Nuclear Research
(European Laboratory for Particle Physics)

Founded in 1954 by 12 European Countries

Today it has 22 member states

At CERN, using special tools (accelerators and detectors) we study:

- The building blocks of matter
  (the elementary particles that all matter in the Universe is made of)
- The fundamental forces that hold matter together



What is the Universe made of

Greek Philosophy

Four basic elements

- Fire
- Air
- Water
- Earth

Chinese Philosophy

Five basic elements

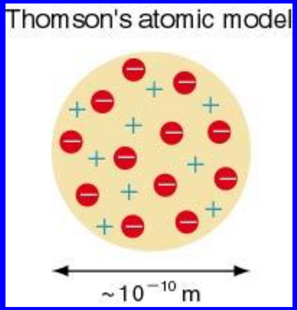
- Water
- Fire
- Wood
- Metal
- Earth

Democritus (460 -371 BC)

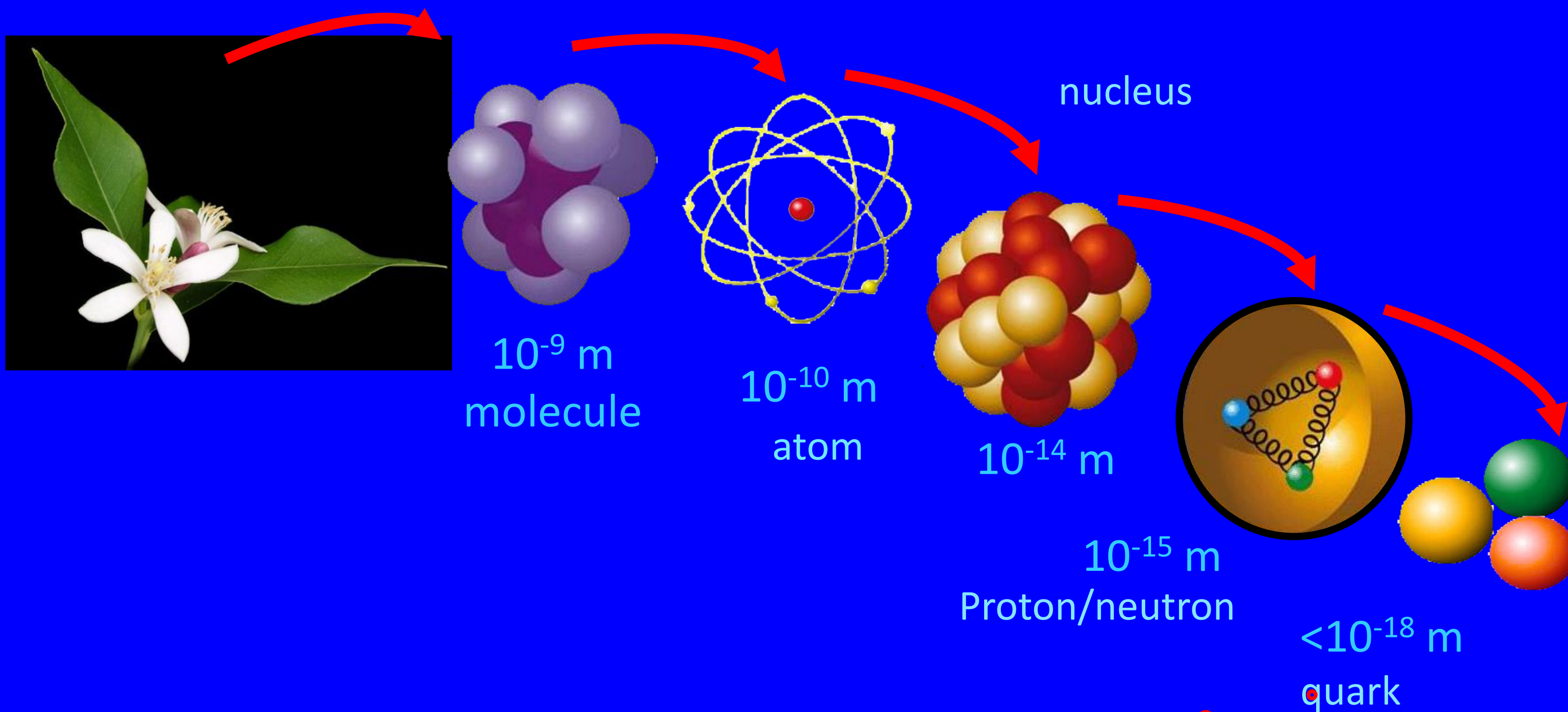
believed that all matter is made of indivisible elements, the atoms

J.J. Thomson

Discovery of the first elementary particle – the electron – with the cathode ray tube (1896)



Thomson's plum pudding model (1904)



Electron, quark $< 10^{-18}$ m = 0.000,000,000,000,000,001 m

Periodic system of the elementary particles

	Quarks		Leptons	
Generation 3	t Top	b Bottom	τ Tau	ν_τ Tau-neutrino
Generation 2	c Charm	s Strange	μ Muon	ν_μ Muon-neutrino
Generation 1	u Up	d Down	e Electron	ν_e Electron-neutrino

↑ mass

charge 2/3 charge -1/3 charge -1 charge 0

In nature : elementary particles of the first generation only

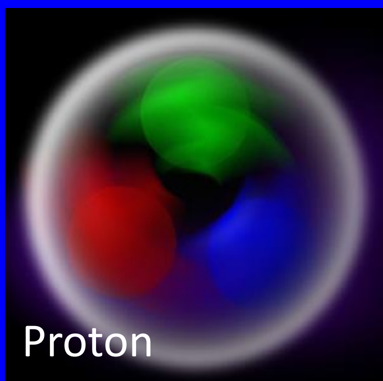
Those of the second and third generation decay to the lighter ones.
They have been seen in cosmic rays or in accelerator experiments

All particles have their antiparticles, with opposite electric charge

Quark Confinement

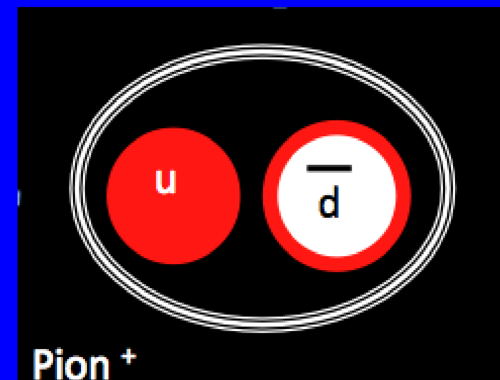
Quarks can not exist free in nature

They can only exist bound inside hadrons



baryons
consisting of
3 quarks

mesons
consisting of
a quark and
an anti-quark



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

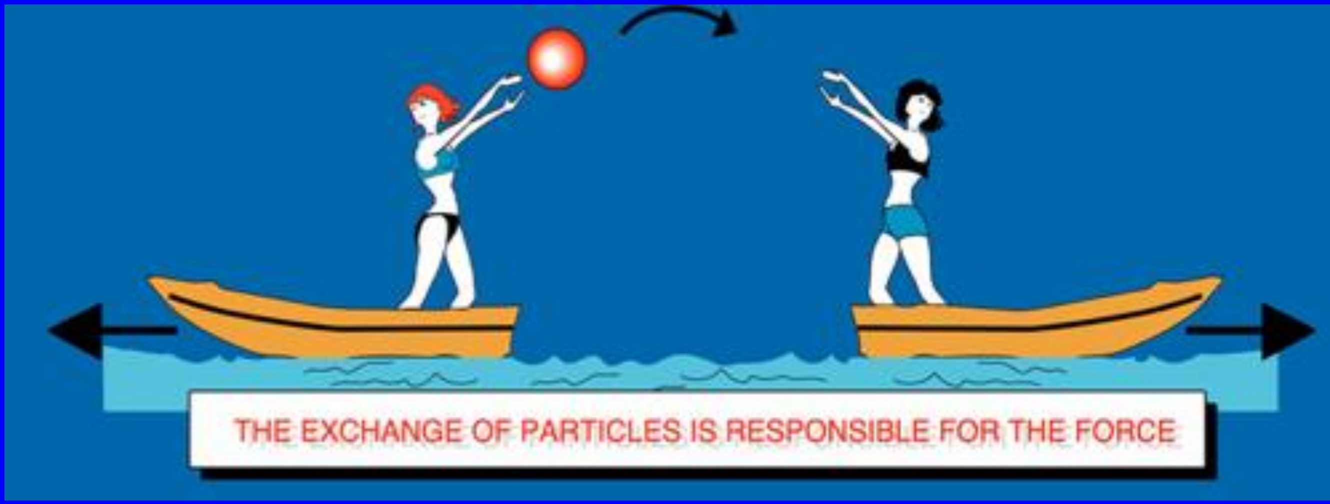
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Concept of interaction - force

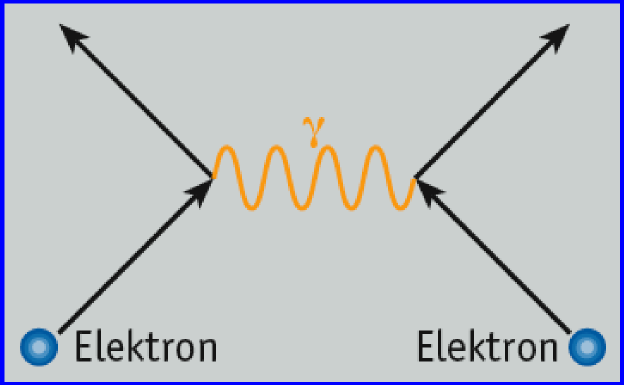
Particles interact with each other (feel each other) with various forces by exchanging special “particles”

and

Forces are mediated by the exchange of “particles”, the force carriers



Example
The interaction of charged particles (attraction or repulsion) is done by the exchange of photons
The photon (γ) is the carrier of the electromagnetic force

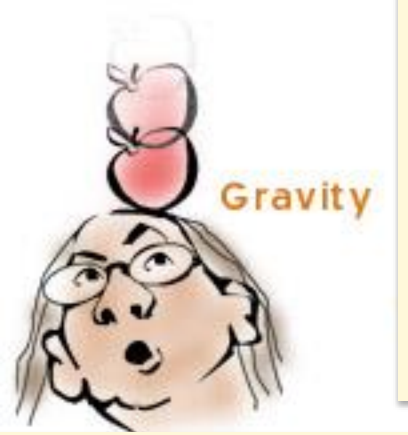


Feynman-Graph

4 Fundamental Interactions

4 Fundamental Interactions

falling apples,
planetary orbits
strength: 10^{-39}
range: infinite
mediator: graviton?



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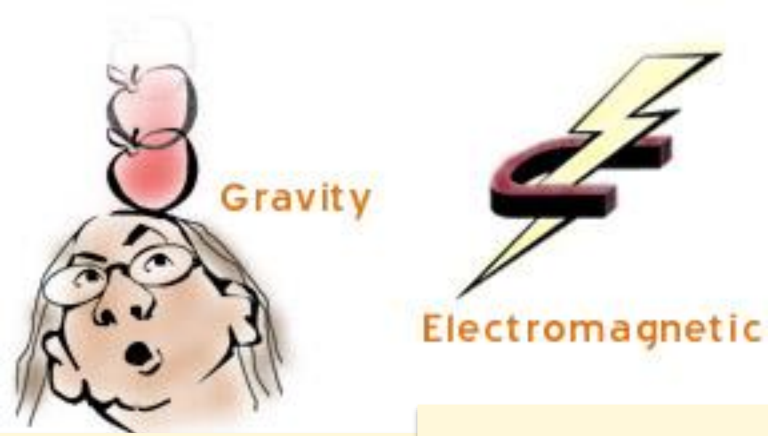

television, magnets,
chemical binding
strength: 1/137
range: infinite
mediator: photon

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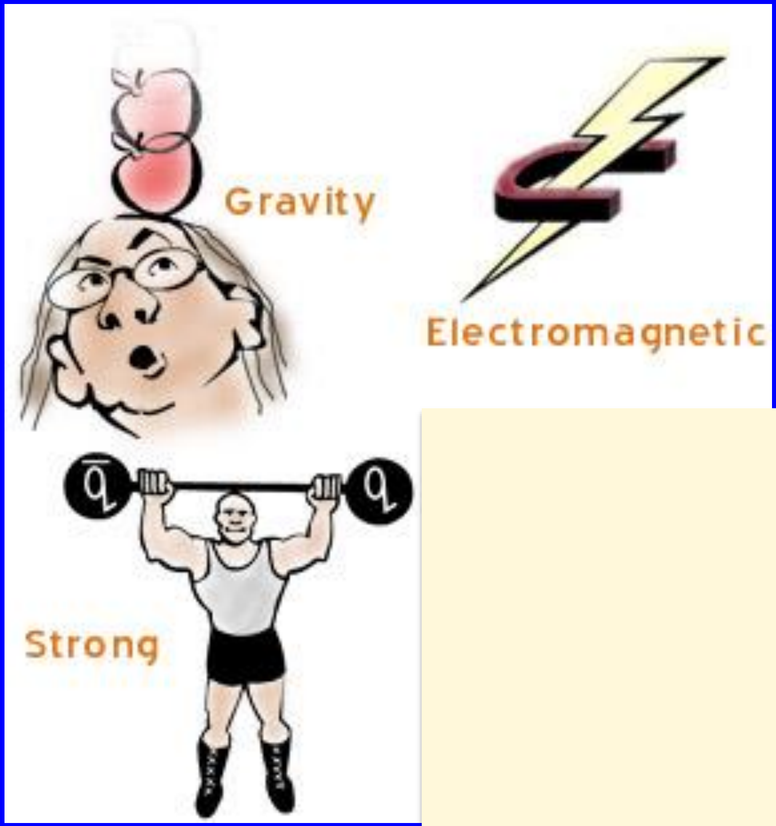

television, magnets,
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strength: 1/137
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nuclear stability,
quark confinement
strength: 1
range: 10^{-15} m
mediator: gluons

4 Fundamental Interactions

falling apples,
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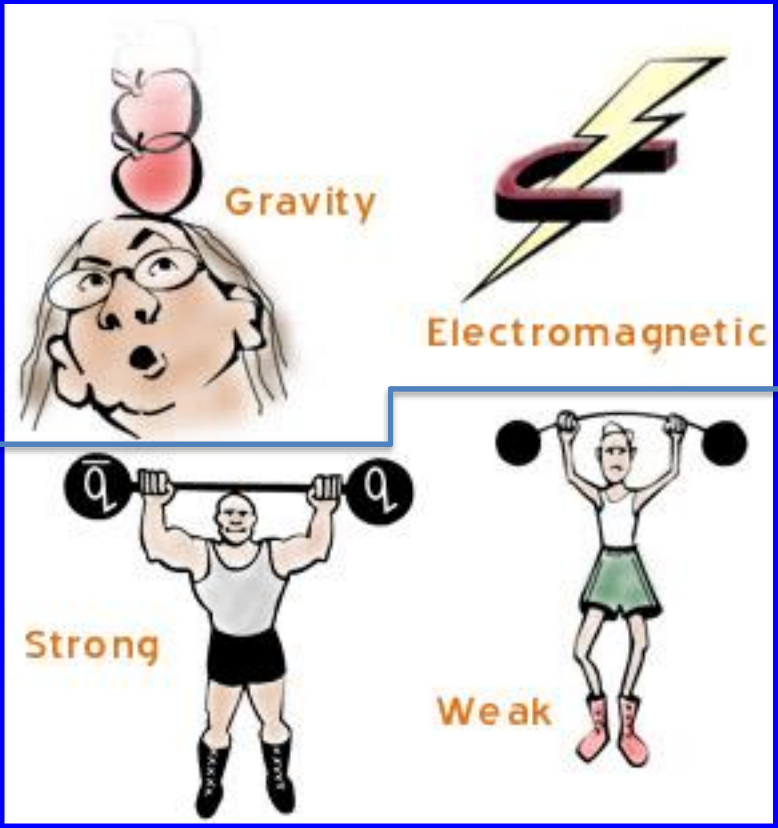
things we can relate to

television, magnets,
chemical binding
strength: 1/137
range: infinite
mediator: photon

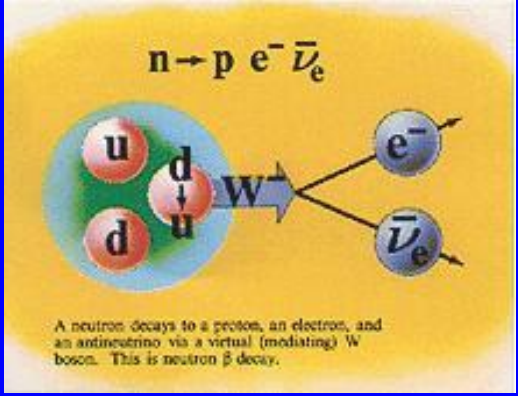


nuclear stability,
quark confinement
strength: 1
range: 10^{-15} m
mediator: gluons

radioactive β-decay
strength: 10^{-5}
range: 10^{-18} m
mediator: W,Z-Bosons

things we cannot relate to

TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0, W+, W- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES

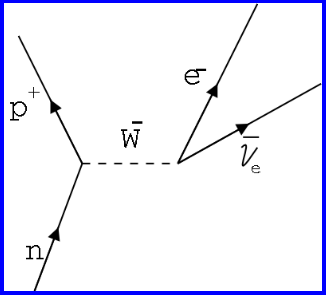


A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

Example : neutron decay (radioactive beta decay)

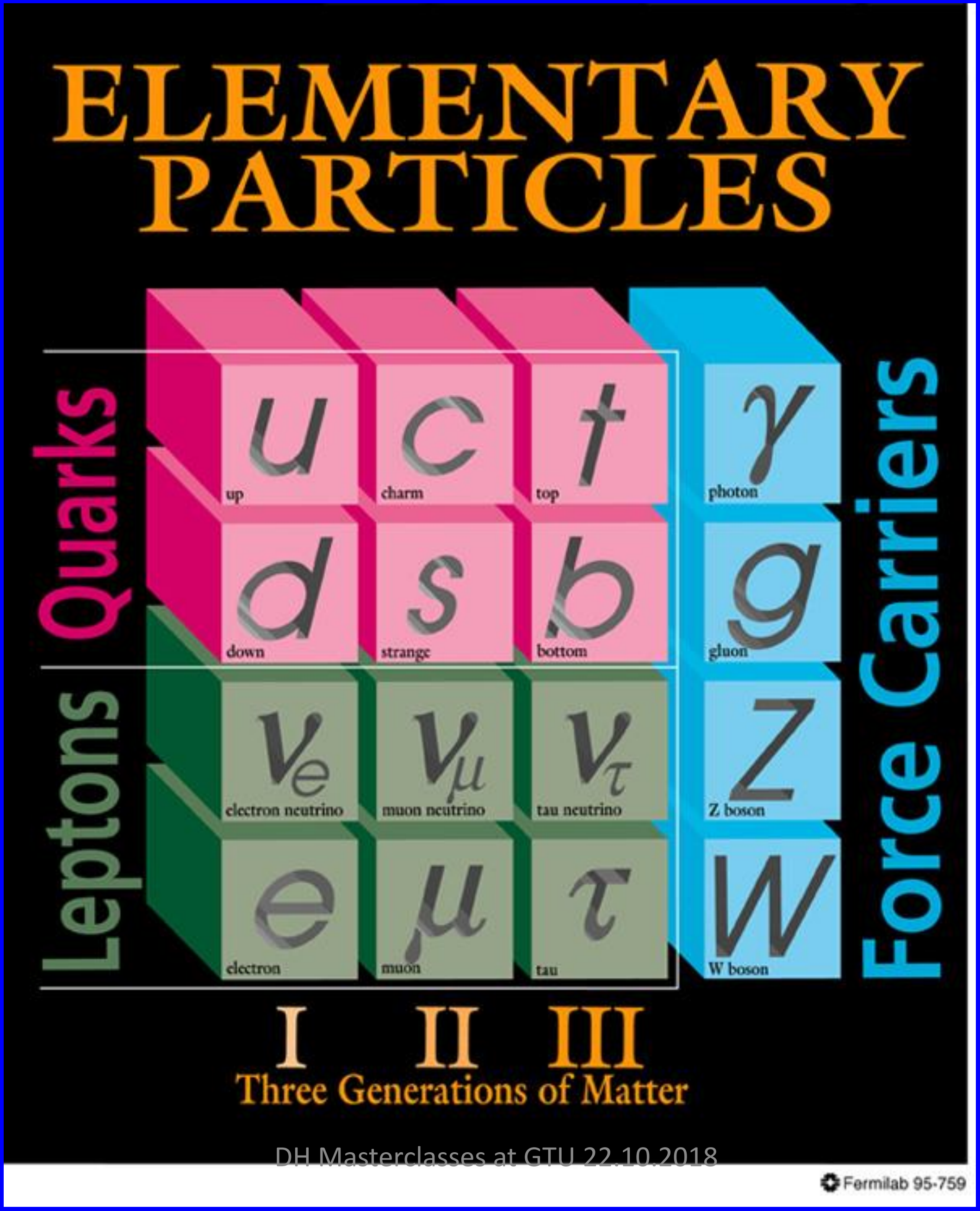
a particle decays into a less massive particle + force-carrier(W) Boson, which then decays into other particles
The force-carrier particle mediating the decay seems to violate conservation of energy because of its high mass
but "virtual" bosons exist so briefly, that no "rule" is broken

Heisenberg uncertainty principle $\Delta E \Delta t \approx h$.



The Standard Model

fermions
Fermi-Dirac
statistics
Spin half-integer
(1/2, 3/2,...)

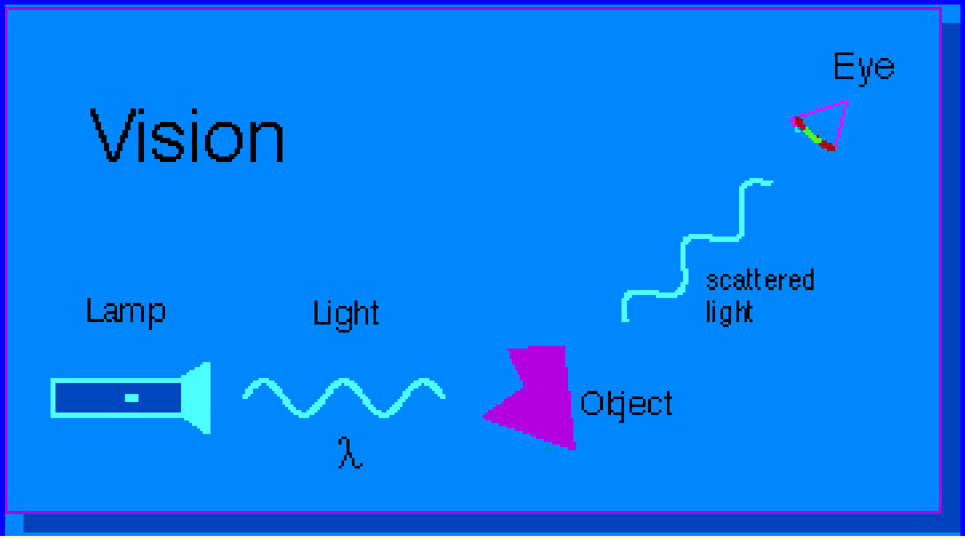


bosons
Bose-Einstein
statistics
Spin integer
(0, 1, 2,..)

The "Right" Light to Look Inside of Things

Vision works by scattering of 'visible' light

λ = 400-700 nm



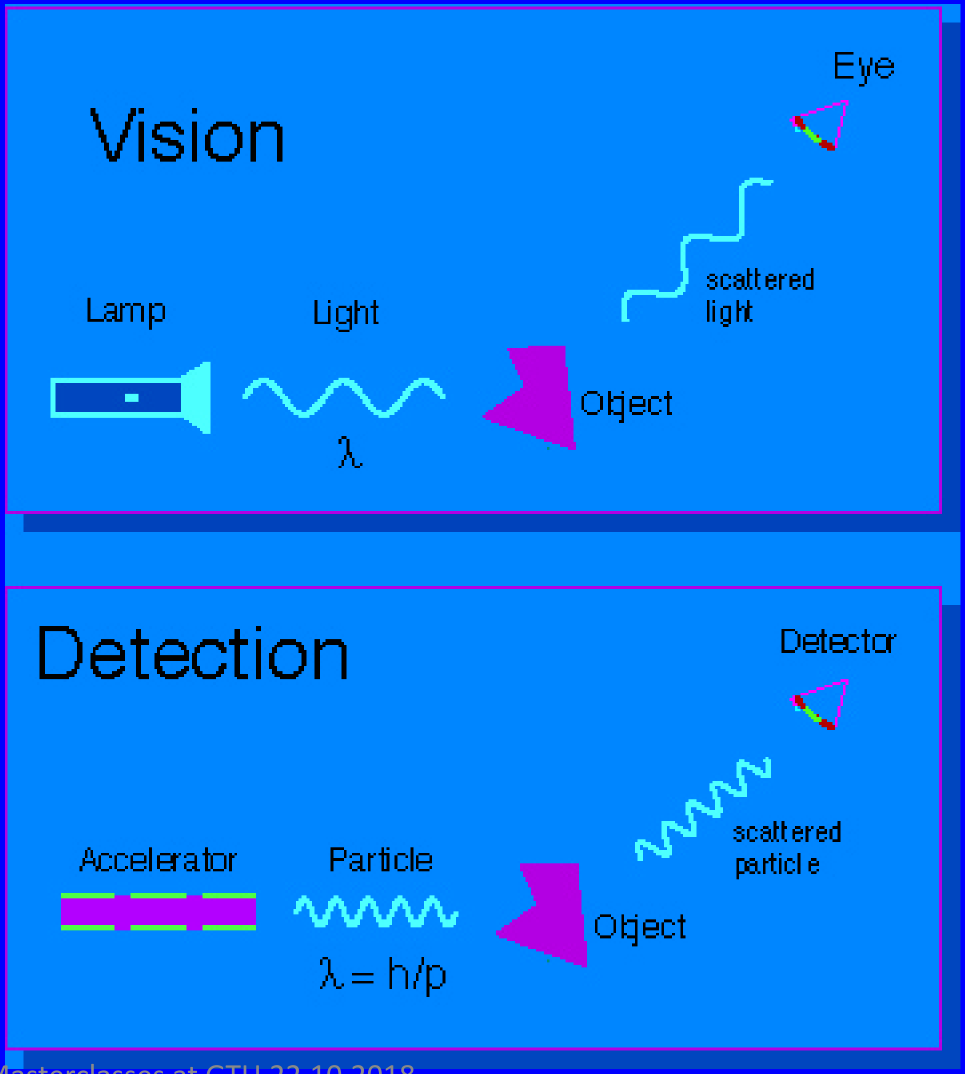
The “Right” Light to Look Inside of Things

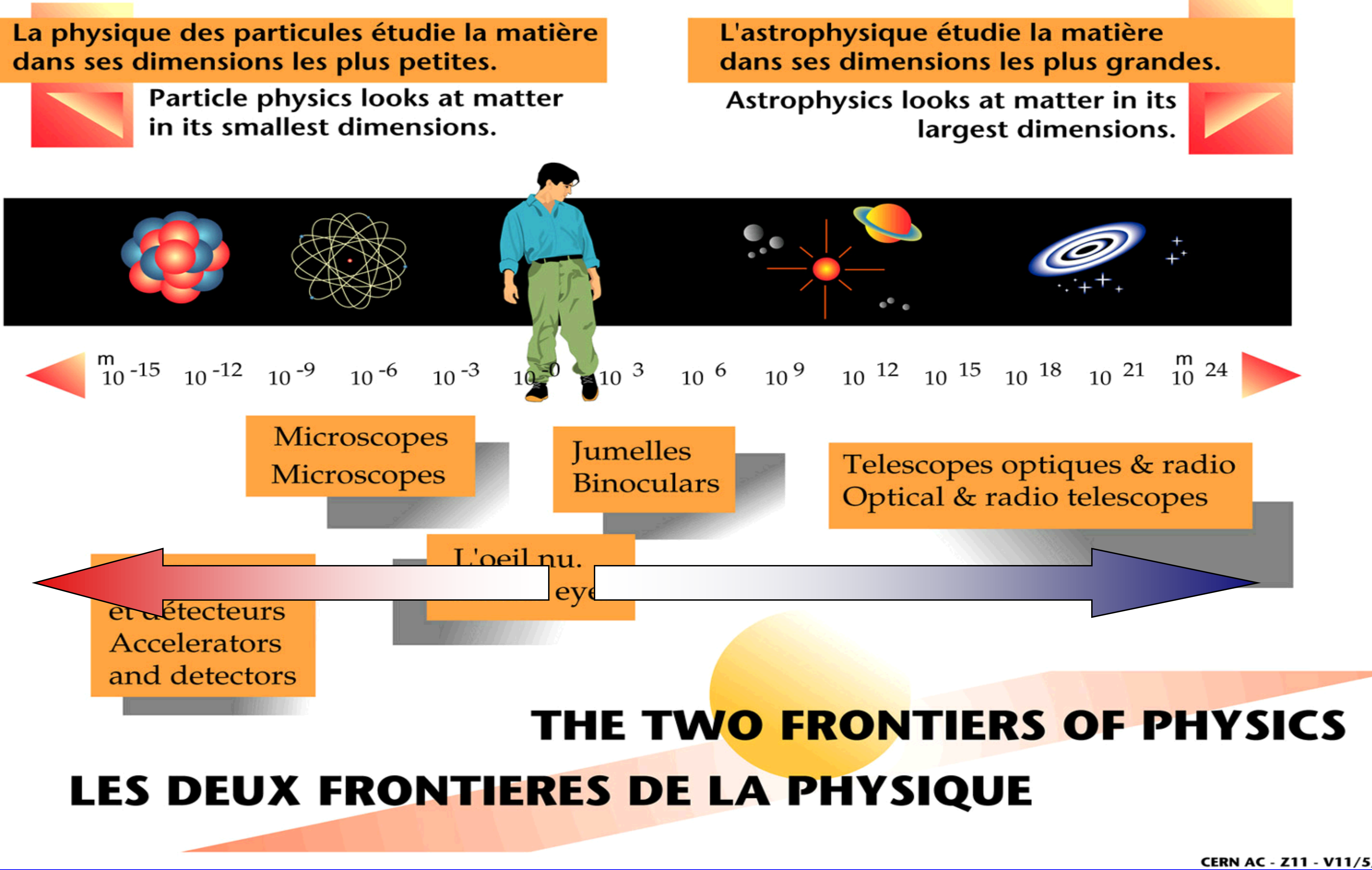
Vision works by scattering of ‘visible’ light

λ = 400-700 nm

“Vision” of even smaller structures via scattering of particles

λ = h/p

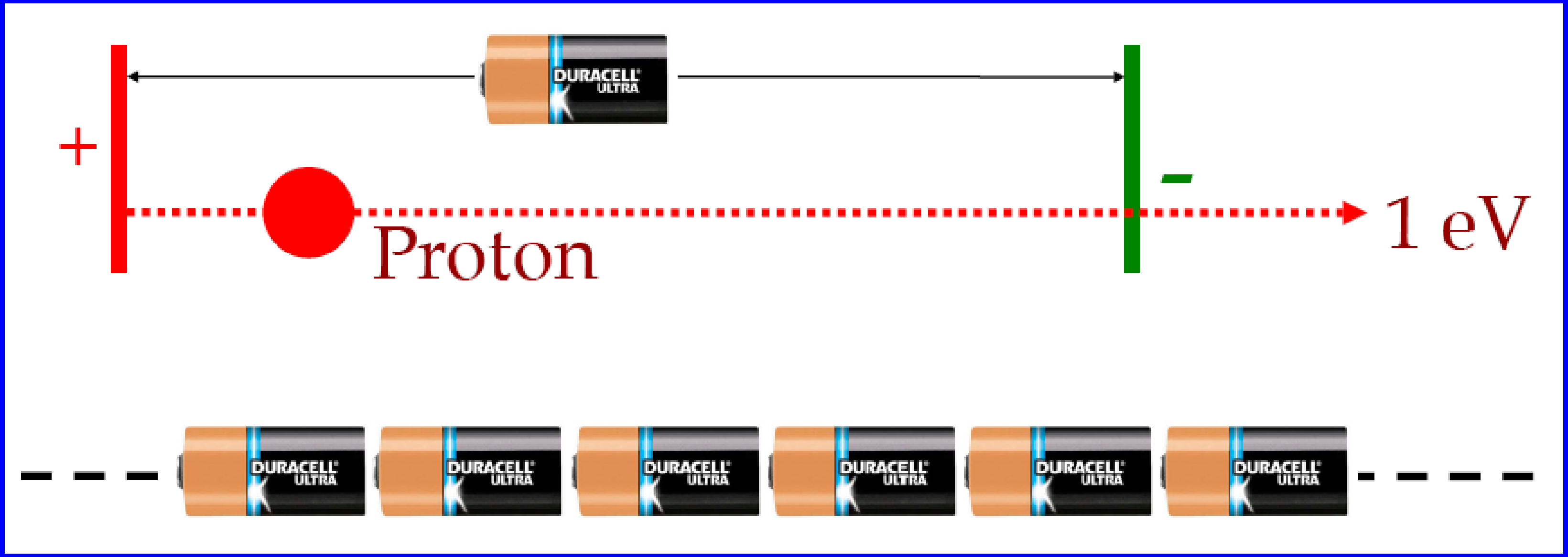




Accelerators are needed for the study of elementary particles and forces

Accelerators

Energy given to a charge in an electric field: E = q•U



For the LHC you would need 2 times 7000 trillion batteries

Units of energy

1 eV = 1.6 x 10 $^{-19}$ Joule

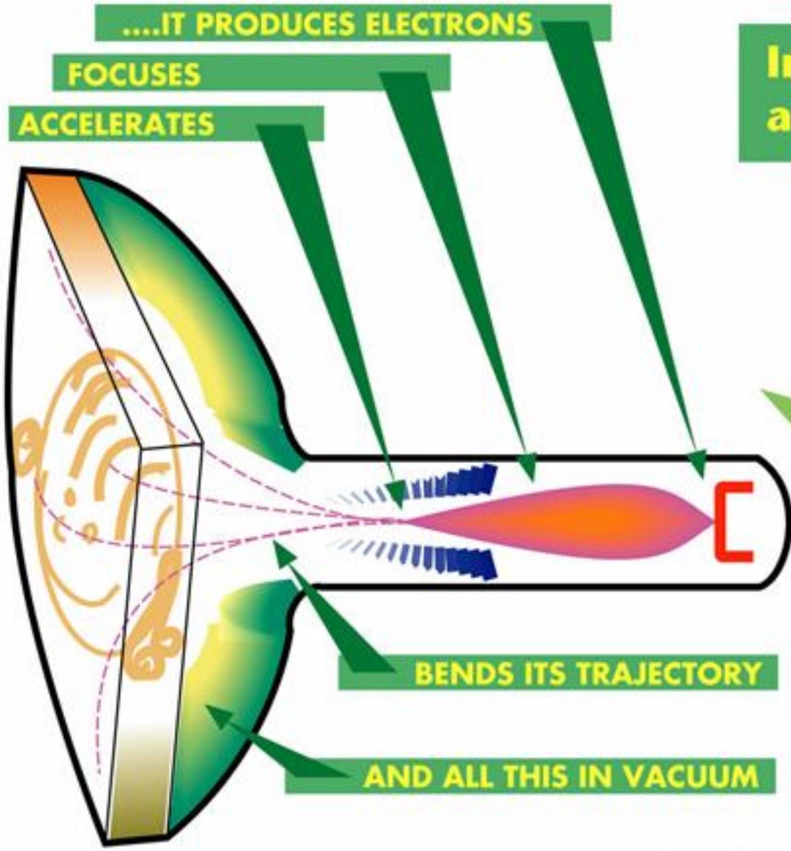
The energy of the elementary charge (that of the electron) accelerated by a potential difference of 1 Volt

1 keV = 10^3 eV = 1000 eV
1 MeV = 10^6 eV = 1 000 000 eV
1 GeV = 10^9 eV = 1 000 000 000 eV
1 TeV = 10^{12} eV = 1 000 000 000 000 eV

Mass – energy equivalence $E = mc^2$

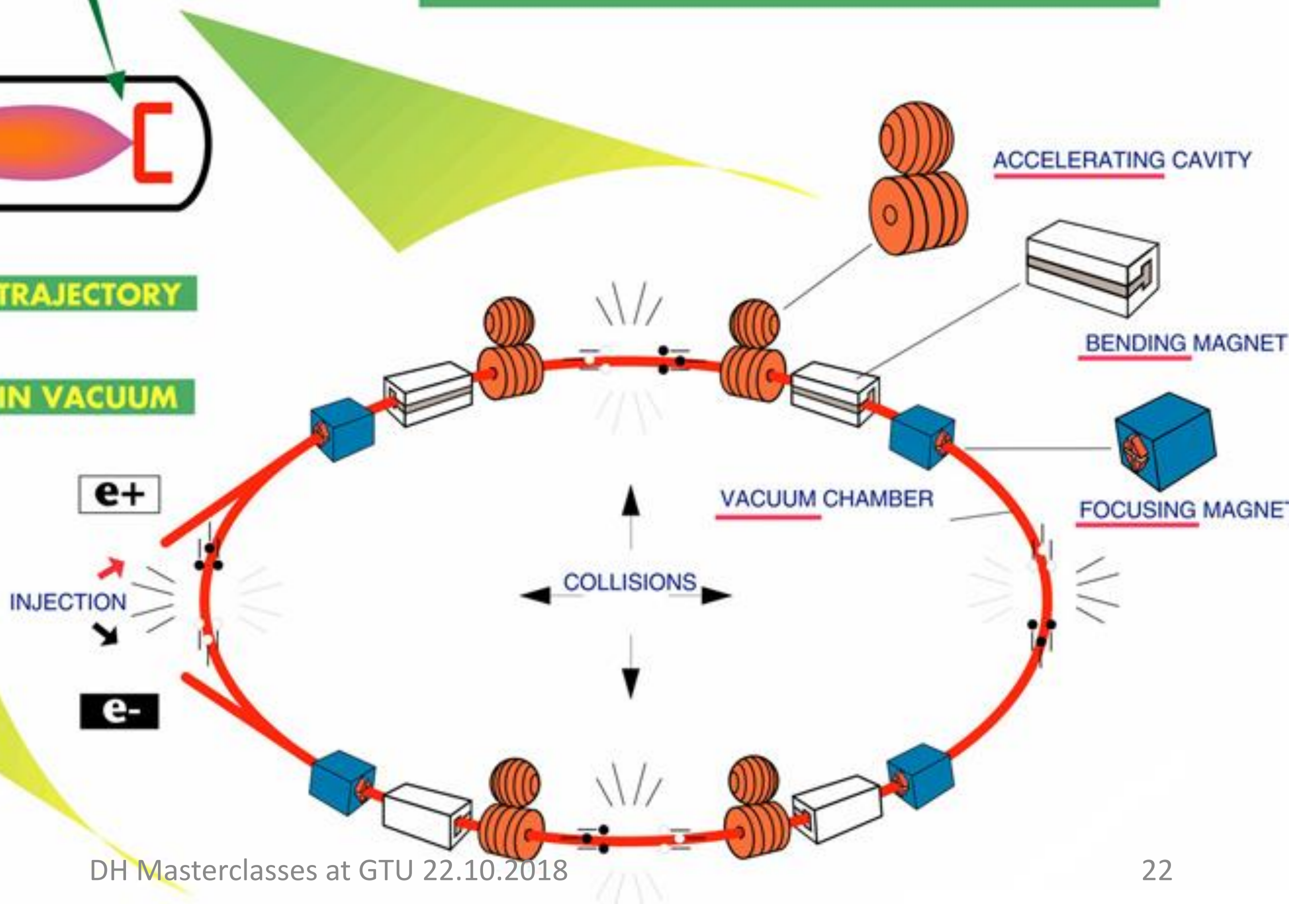
c=1 natural units
mass expressed in units of energy

DID YOU KNOW YOUR TELEVISION SET IS AN ACCELERATOR ?

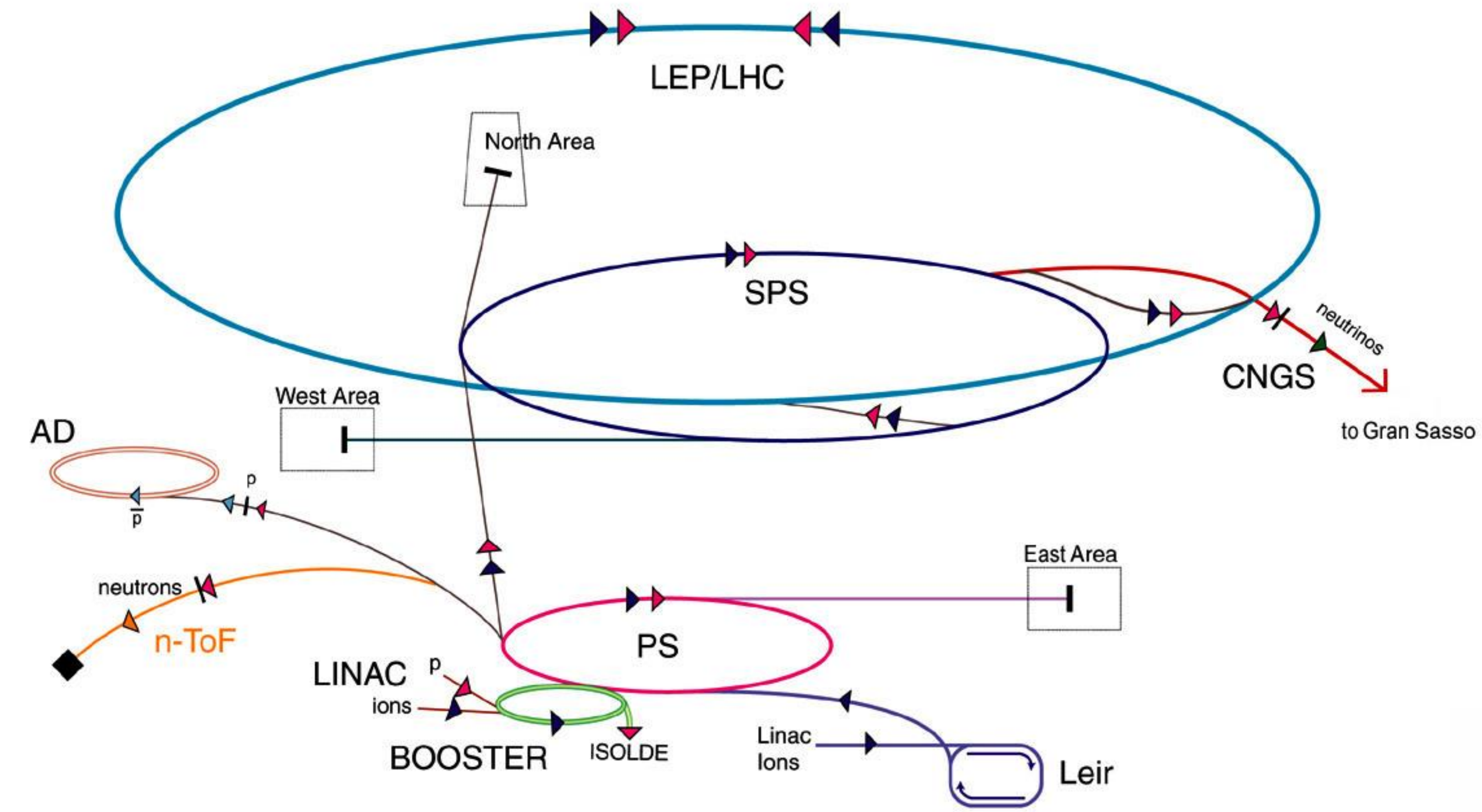


In your TV set, the electrons are accelerated to 20000 volts.

In LEP, they are accelerated to 100 000 000 000 volts.



CERN's mission : to provide accelerators for Particle Physics experiments

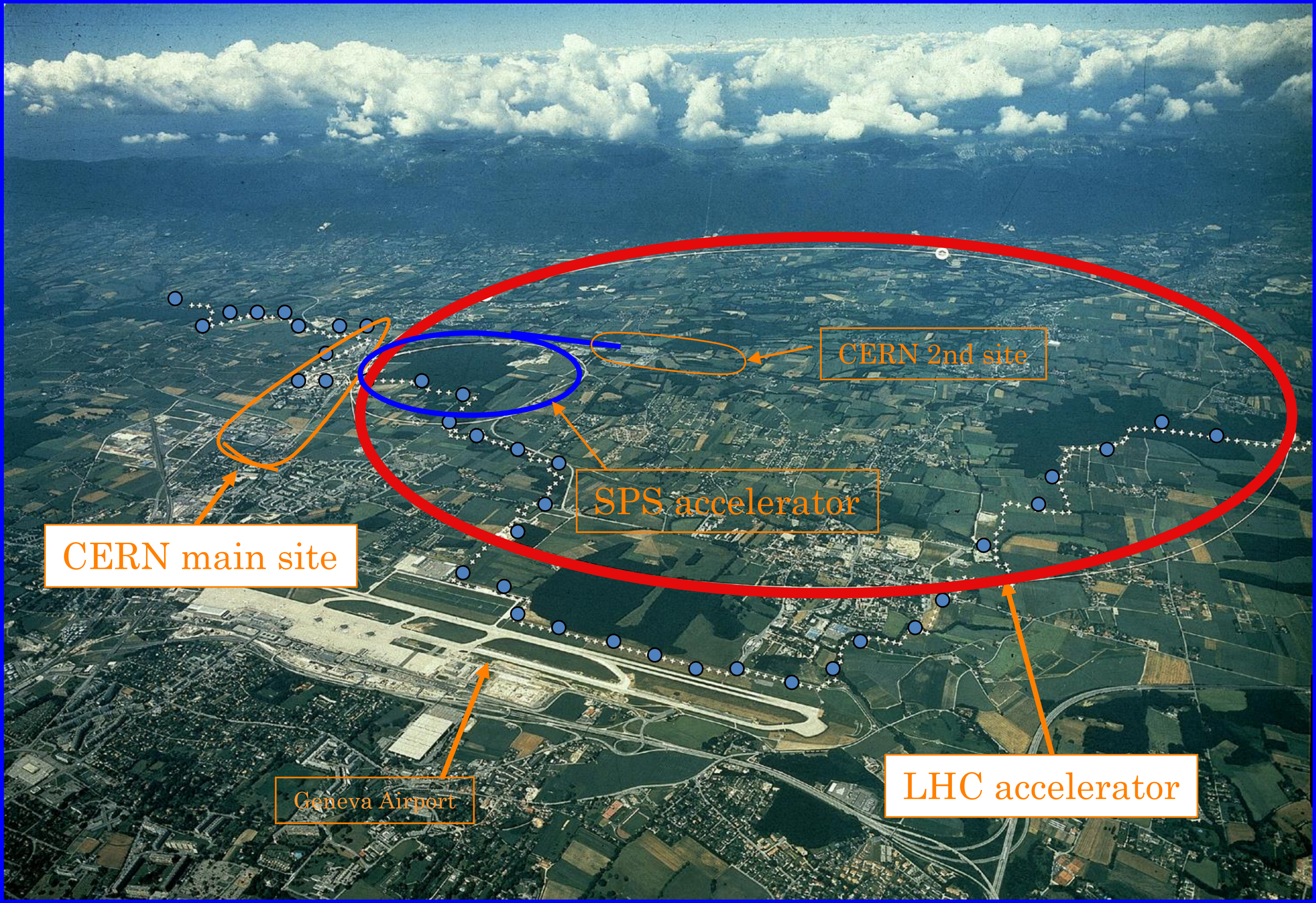


p (proton)
ion
neutron

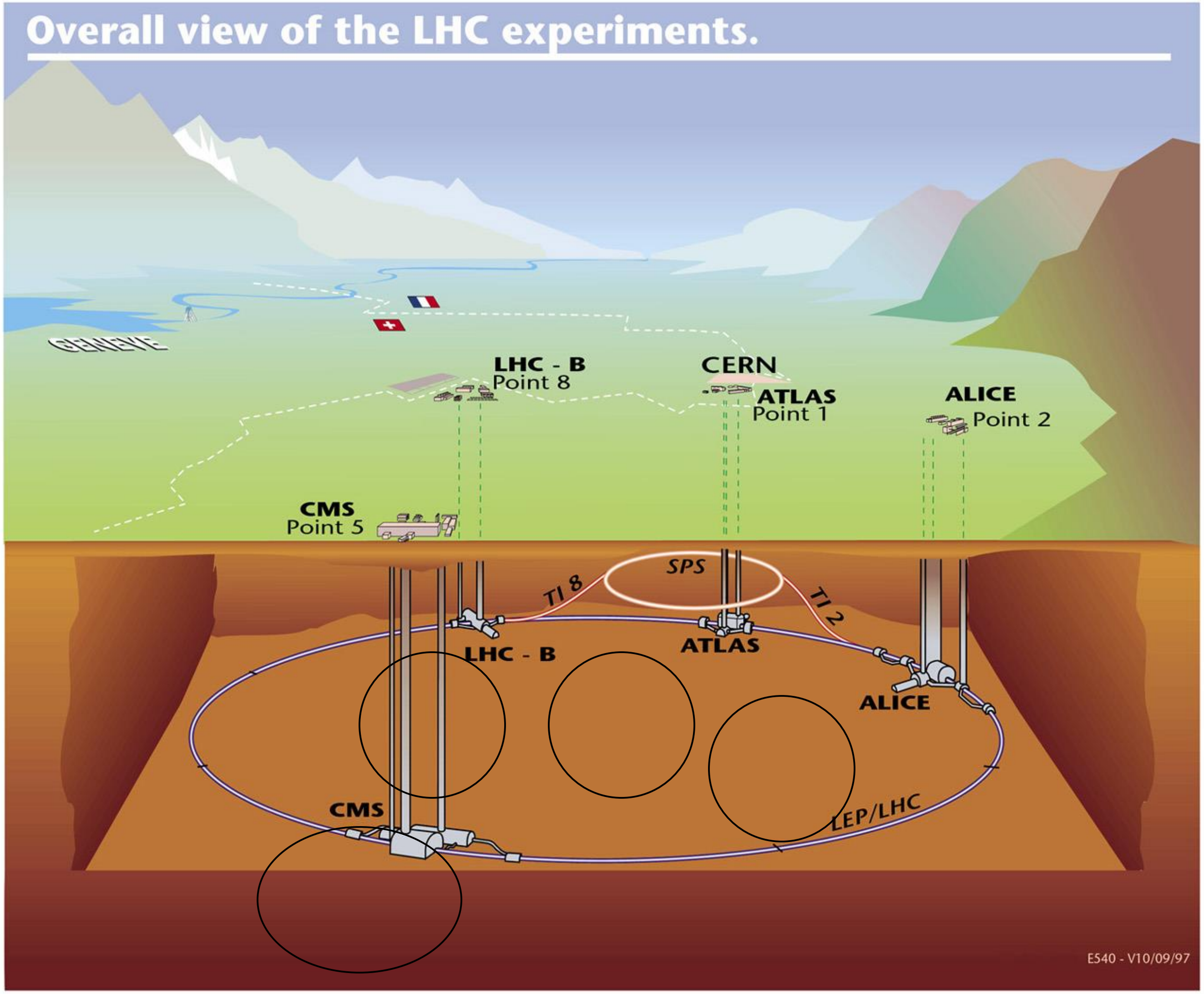
p̄ (antiproton)
proton/antiproton conversion
neutrino

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS Cern Neutrinos Gran Sasso


CERN 2nd site
SPS accelerator
CERN main site
Geneva Airport
LHC accelerator

The Large Hadron Collider (LHC)



The largest accelerator in the world, in a ring of 27 km circumference

At LHC two beams of protons collide at the highest accelerator energy (13 TeV now and will reach 14 TeV)

LHC is the coldest installation in the universe: its superconducting magnets, cooled with liquid helium, operate at -271^{o} C (1.9 K, just above absolute zero)

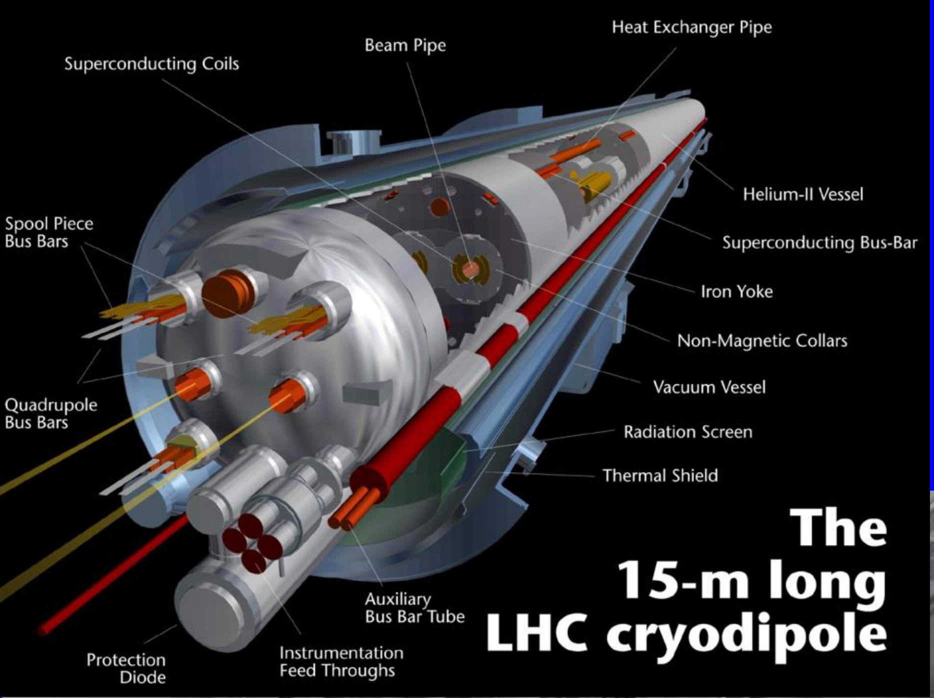
The LHC is located in a tunnel 100 m underground

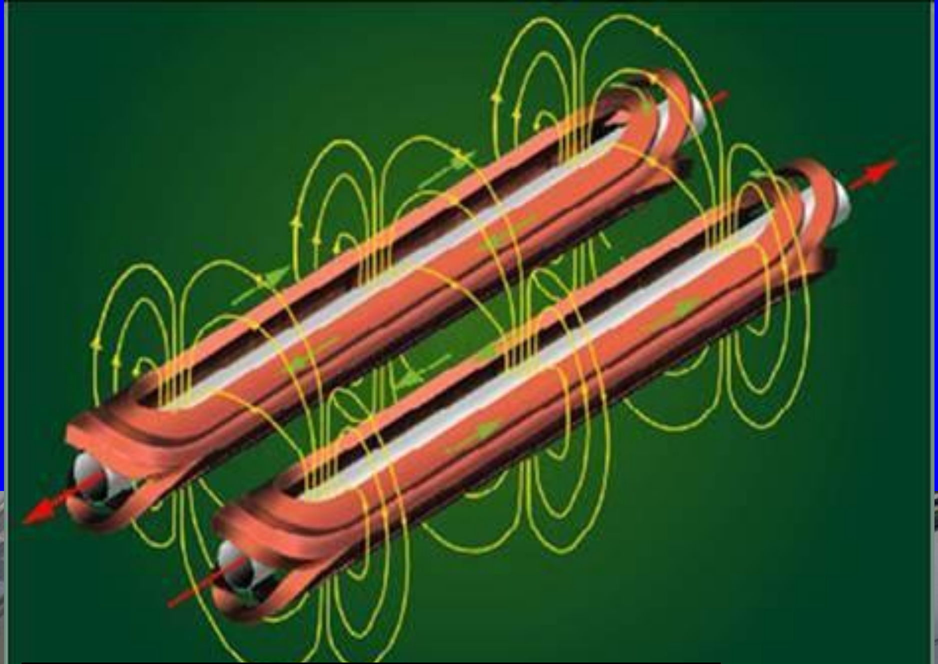
8 radiofrequency cavities for each beam, installed in groups of 4 in cryomodules, accelerate the beams

frequency : 400 MHz

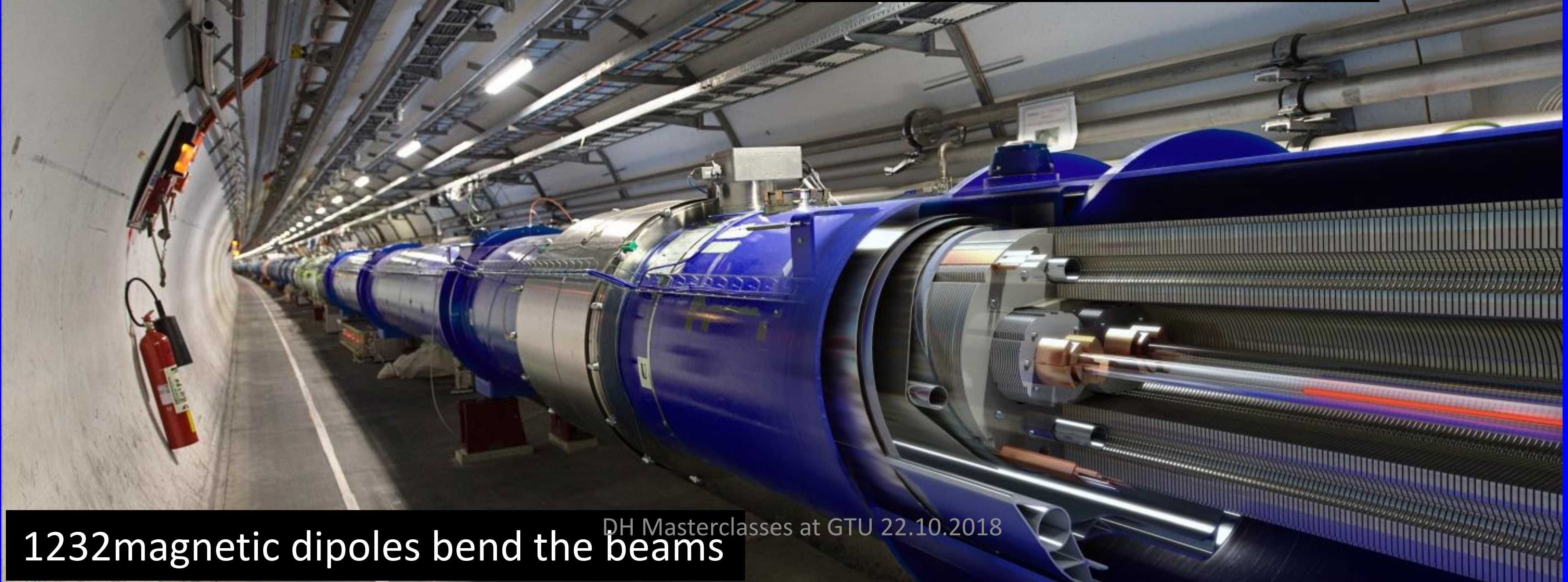
superconductive, cooled at 4.5 K

The beams circulate inside beam pipes with very high vacuum : 10^{-13} atm



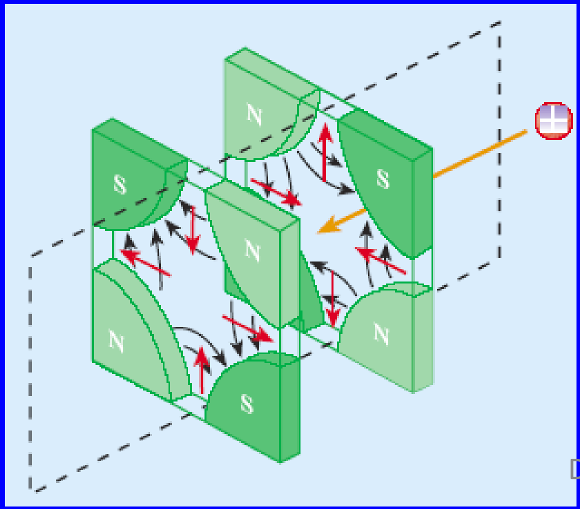


8.3 Tesla for 7 TeV ~ 12 000 A

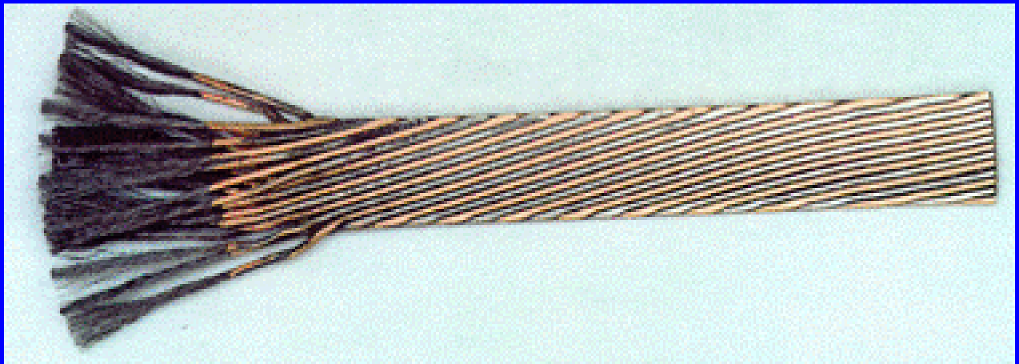


1232magnetic dipoles bend the beams

858 quadrapole magnets focus the beams

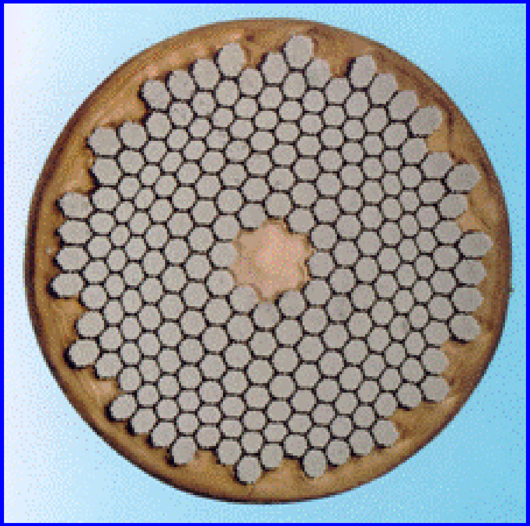


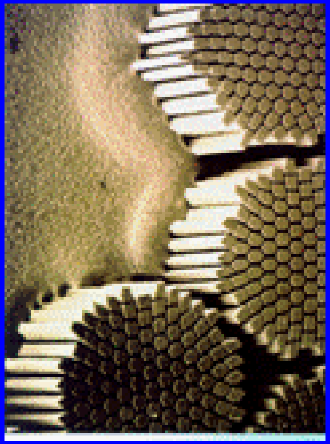
Superconductive cable : zero resistance, no energy loss in form of heat



- 1200 tons/ 7600 km supeconductive caible
- Total length of the filaments: 10 times the distance earth- sun

Rutherford cable : 36 strands



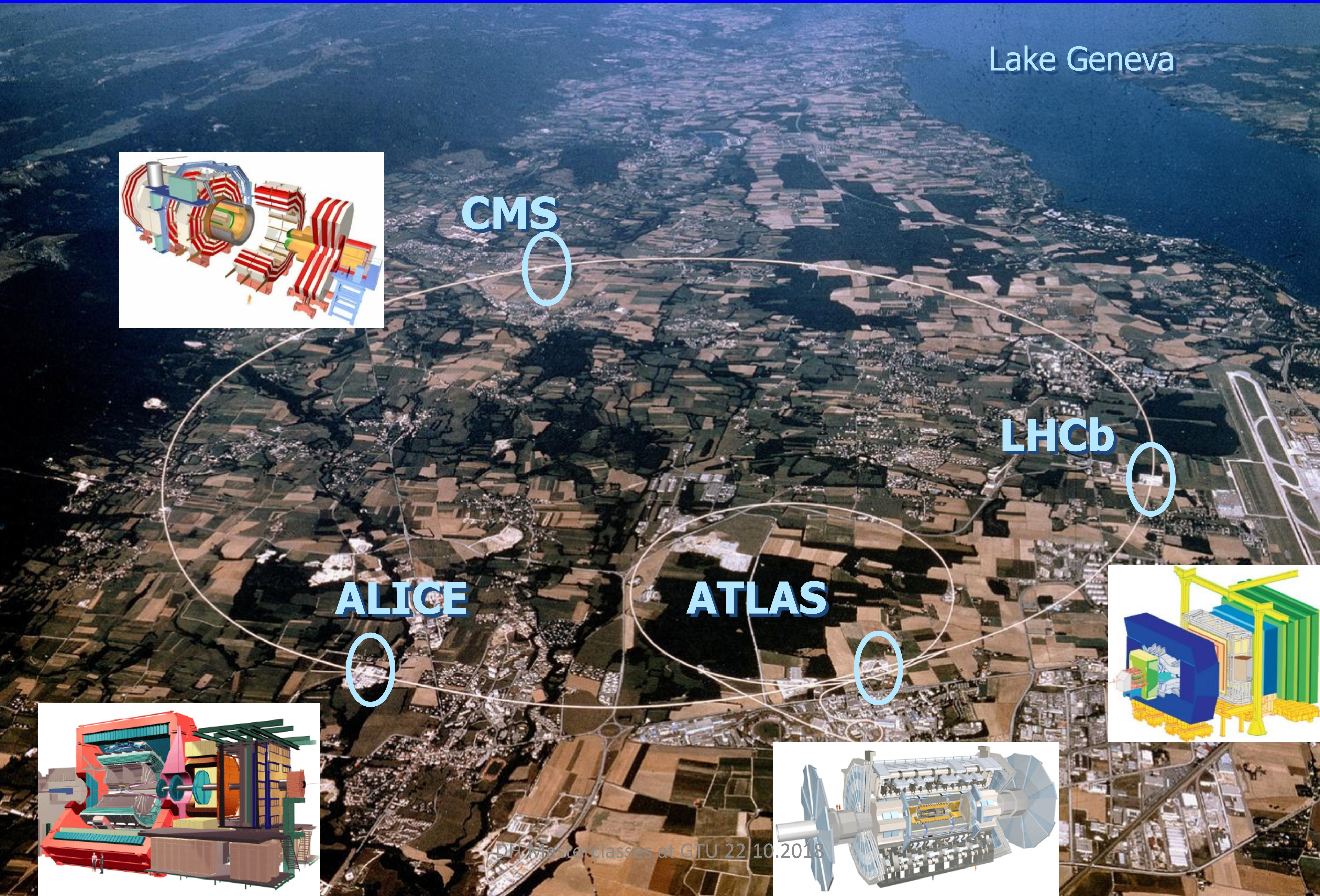


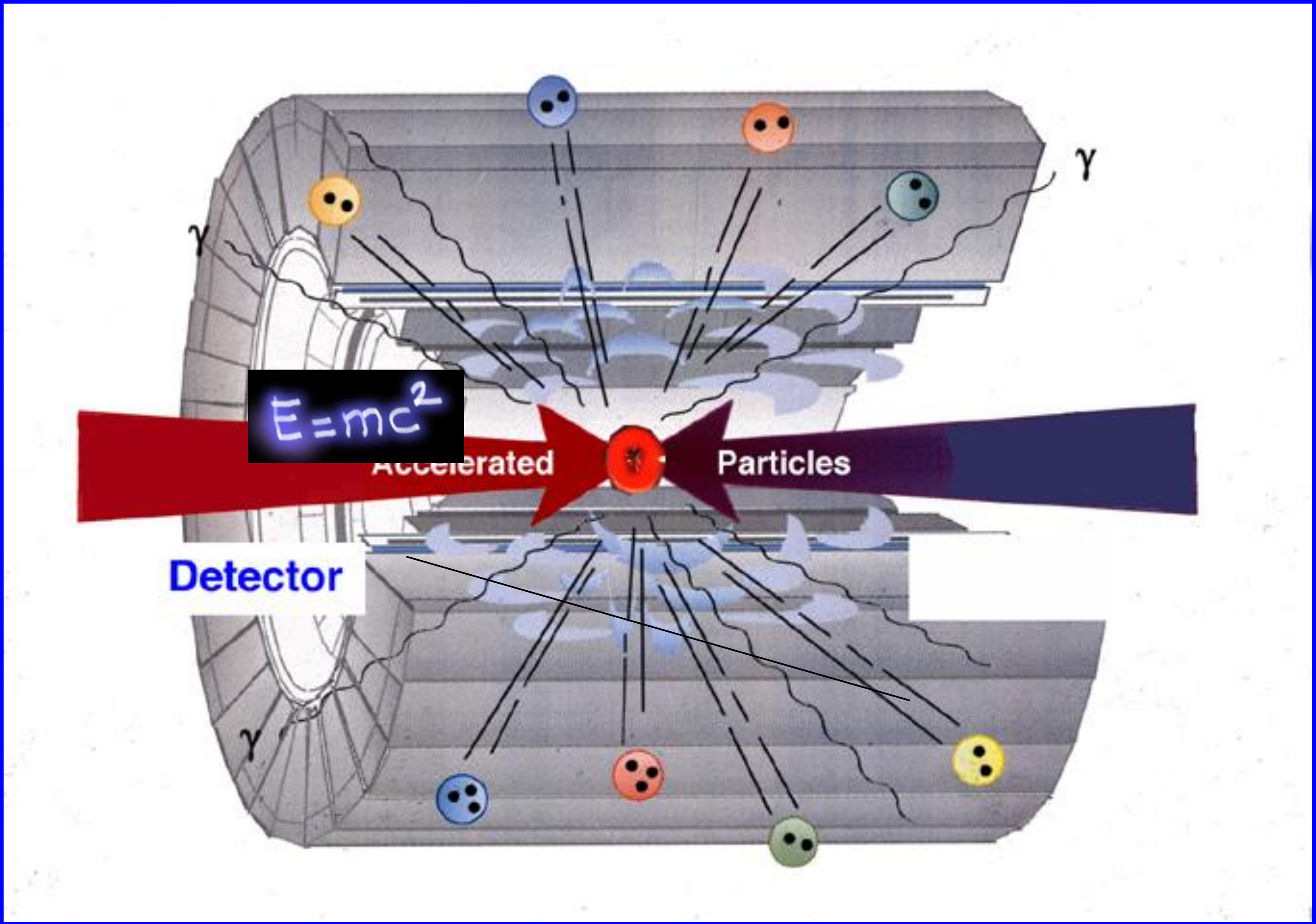
Cryogenic system

- 5000 tons of liguid Helium cool the magnets to 1.9 K (-271°C)
- 10000 tons of liguid Nitrogen coool the gaseous Helium to 80 K

Each wire (d = 0.825 mm) ~ 6500 filaments (very thin wires d = 8 µm)
Niobium-Titanium(+ 0.5 µm Copper)

4 big experiments are installed at LHC





1) We concentrate energy on protons by accelerating them

2) We collide protons – their energy is liberated at the point of collision

3) New particles are produced - transformation of energy to mass

We "see" these new particles and measure their characteristics with detectors

Particle Detectors

- They “see” the particles produced from beam-beam or beam-target collisions
- The detection is based on interaction of the particles with the detector material and results –in most cases- in the production of an electrical signal

Various types of detectors

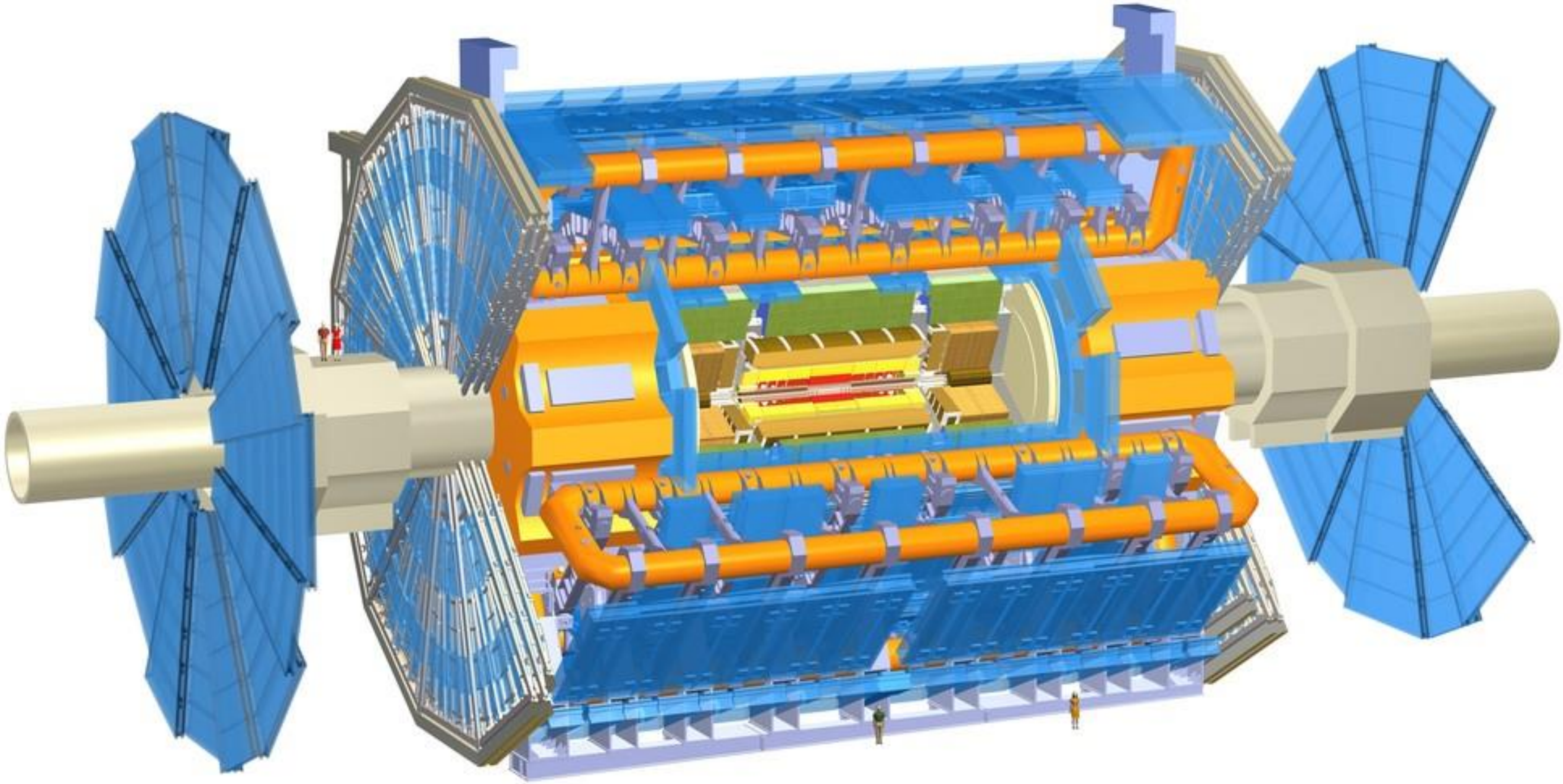
Solid state detectors (semiconductors, e.g. Si)
Gaseous detectors
Scintillators …

They convey information about

The particle energy (calorimeters)
The particle type (particle identification)
The particle trajectory (tracking devices)

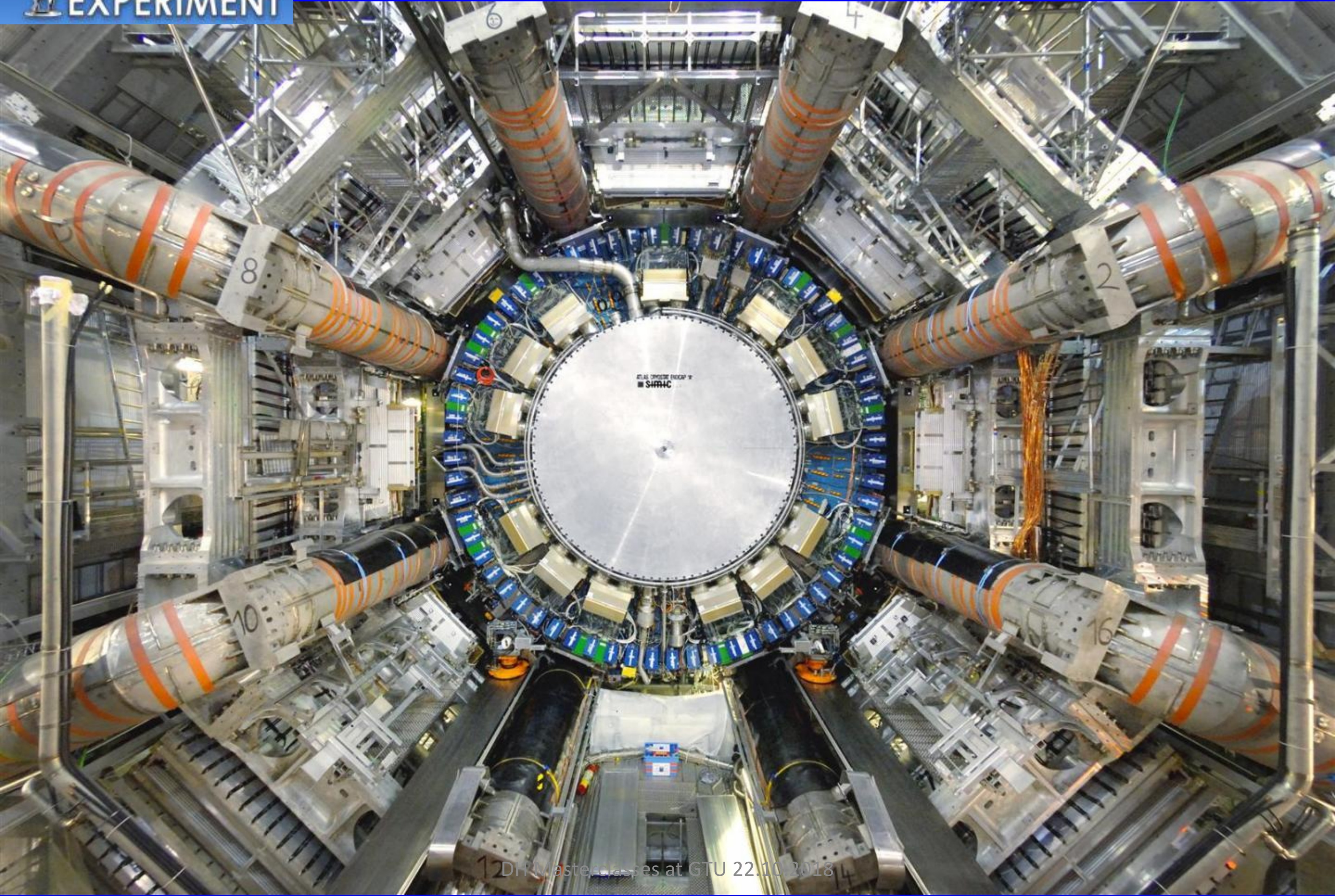
Most particles produced from the collisions have a very short life – they decay immediately and we see their “children”, their decay products.
Particles we “see” in our detectors can be : electrons, photons, muons, pions, kaons, protons and hadron jets (originating from quarks)

ATLAS EXPERIMENT

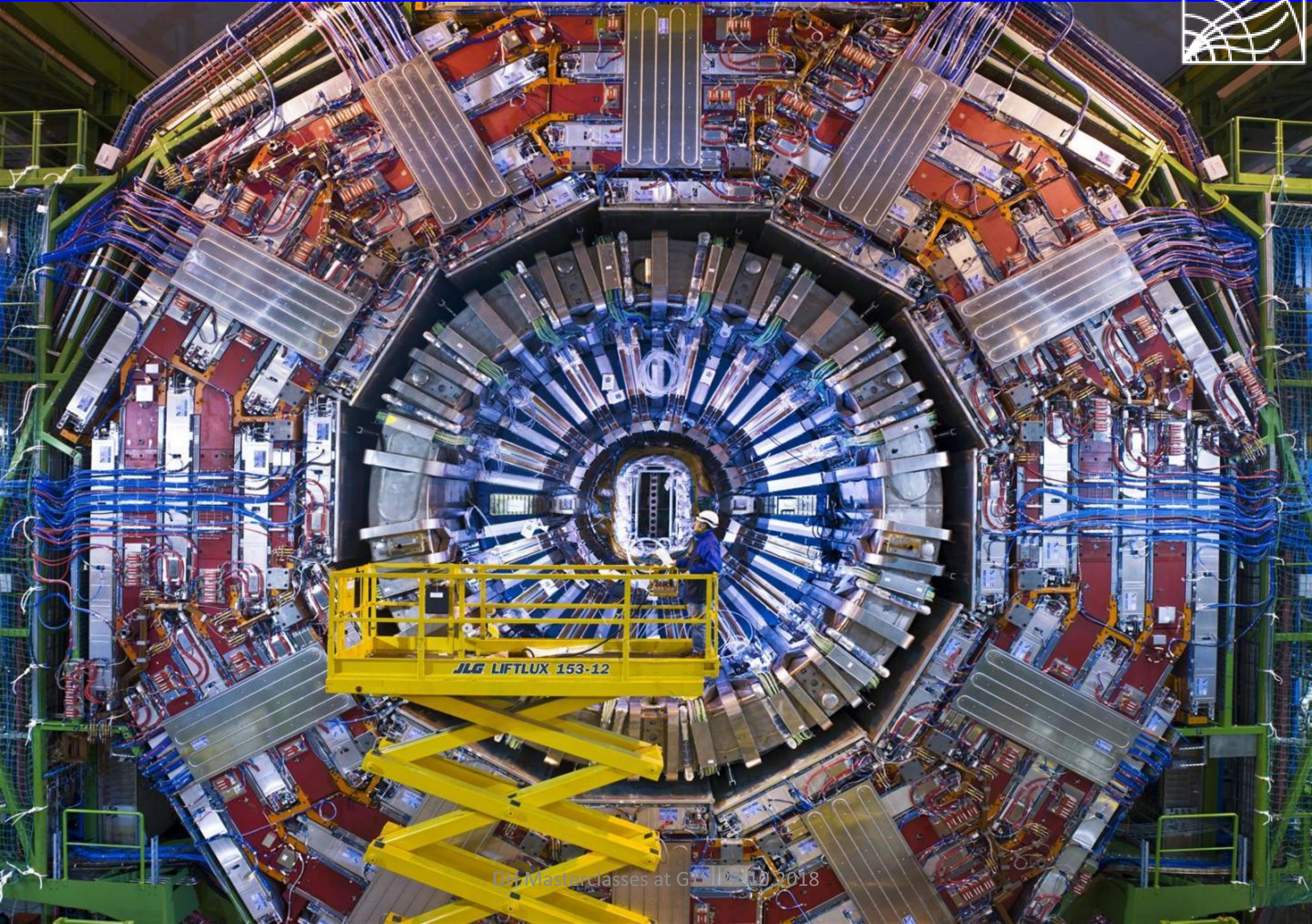


25 m x 25 m x 46 m 7000 tons

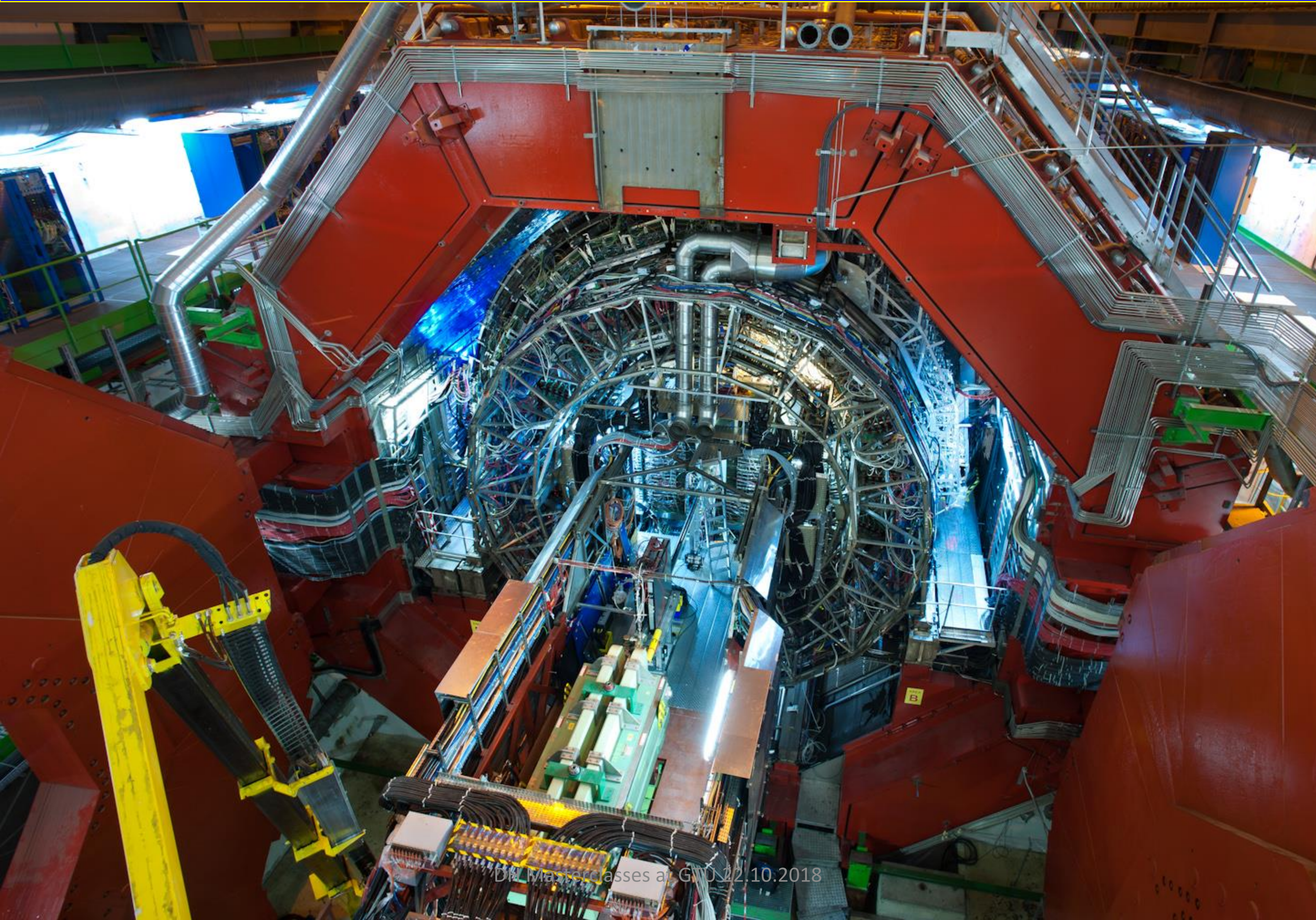
ATLAS : A Toroidal LHC ApparatuS



CMS : Compact Muon Solenoid



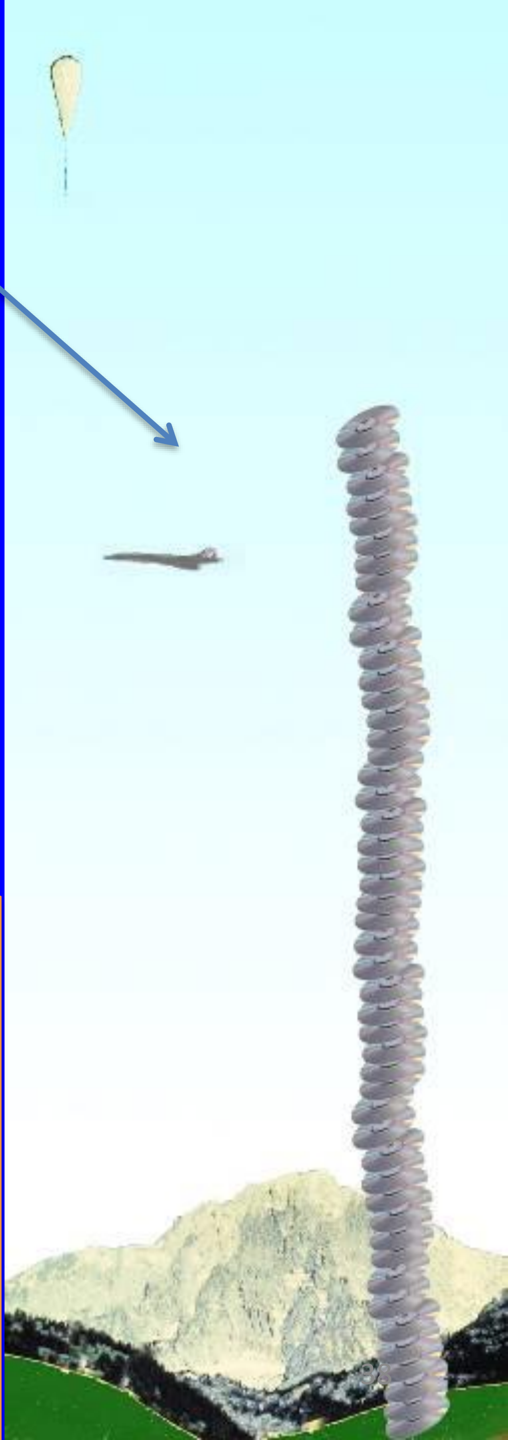
ALICE : A Large Ion Collider Experiment



LHCb : Large Hadron Collider beauty experiment

For every collision the detectors produce electrical signals which are then transformed into digital information. This is read out and recorded by computers.

20 km CD per year from the LHC experiments



The GRID

Thousands of computers in hundreds of computer centres all around the world are connected to the Grid: they share their processing power and their storage capacity to analyse the data from the LHC experiments.

Some facts about LHC

- protons in LHC in bunches (of 100 billion p) every 25 ns;
- accelerated from 450 GeV to 4 TeV
- reaching a speed of 99.9999991% the speed of light
- 40 million times/s bunches pass each collision point
- The protons go around the LHC ring 11245 times/s
- 31.2 MHz crossing rate
- 20 collisions expected in average (from 100 on 100 billion p)
- 600 million proton collisions per second
- After filtering, 100 collisions of interest per second
- 1 Megabyte of data digitised for each collision
- recording rate of 0.1 Gigabytes/sec
- 10^{10} collisions recorded each year
- >10 Petabytes/year of data

1 Megabyte (1MB)
A digital photo

1 Gigabyte (1GB) = 1000MB
A DVD movie

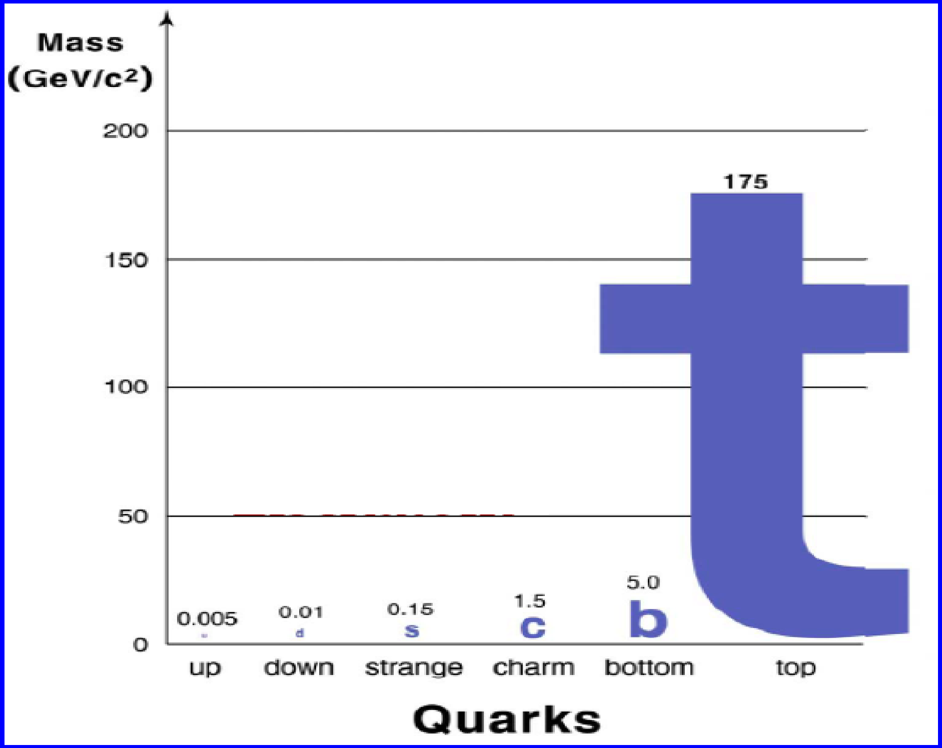
1 Terabyte (1TB) = 1000GB
World annual book production

1 Petabyte (1PB) = 1000TB
Annual production of one LHC experiment

1 Exabyte (1EB) = 1000 PB
World annual information production

With LHC we are looking for answers to the unanswered questions

Why do particles have mass?
Why do they have so different masses?



The Standard Models foresees that elementary particles have zero mass.

The Higgs field fills the Universe and the interaction of particles with it gives them their mass, big or small, depending on the strength of the interaction.
The Higgs field is connected with the Higgs boson.

Probable answer : the Higgs* mechanism, which also foresees the existence of the elusive Higgs particle.

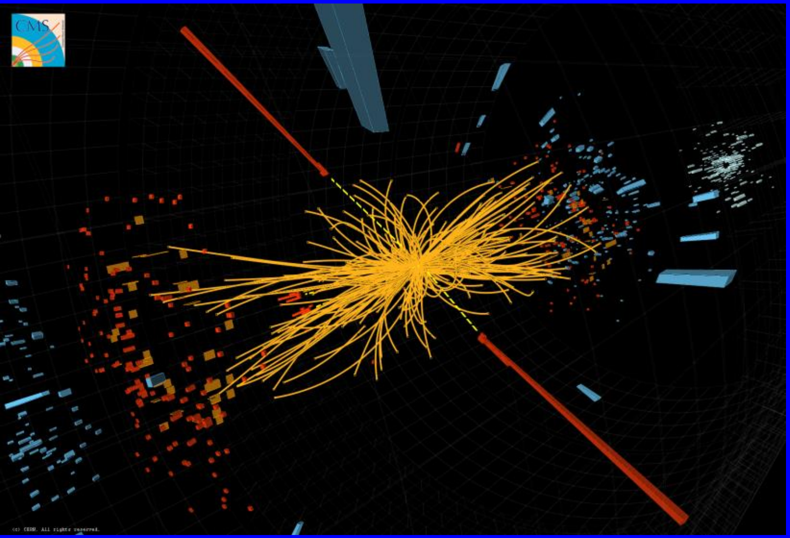
Peter Higgs visiting the ALICE experiment
CERN Open Day - April 2008

***Englert-Brout-Higgs-Guralnik-Hagen-Kibble** mechanism

Higgs update seminar – CERN - 4 July 2012

a historic day for CERN

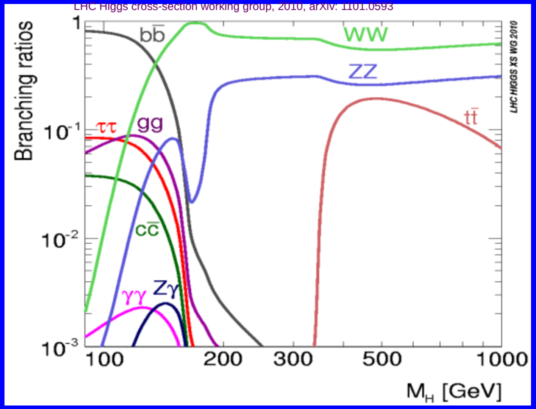
Discovery of a new boson announced



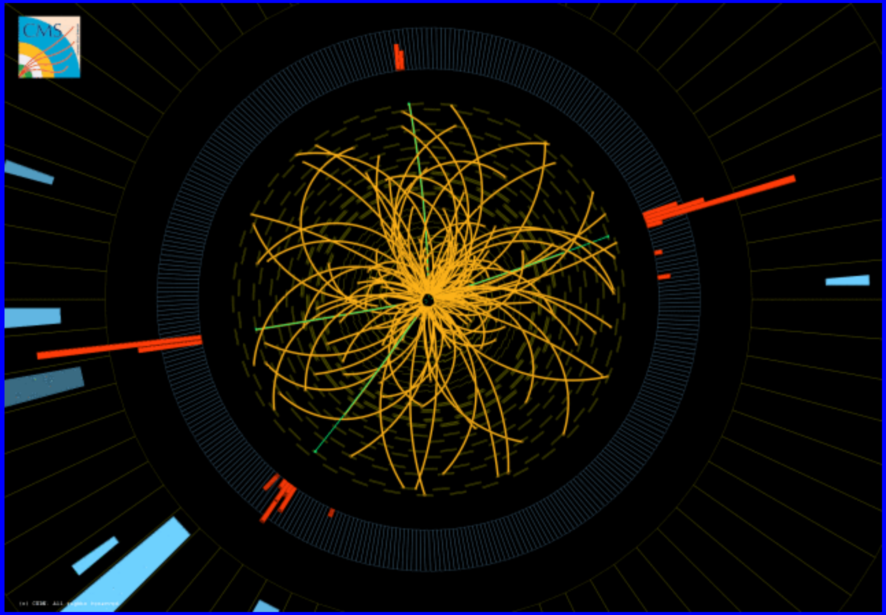
Proton-proton collision with 2 photons

Higgs boson search : we look for its decays

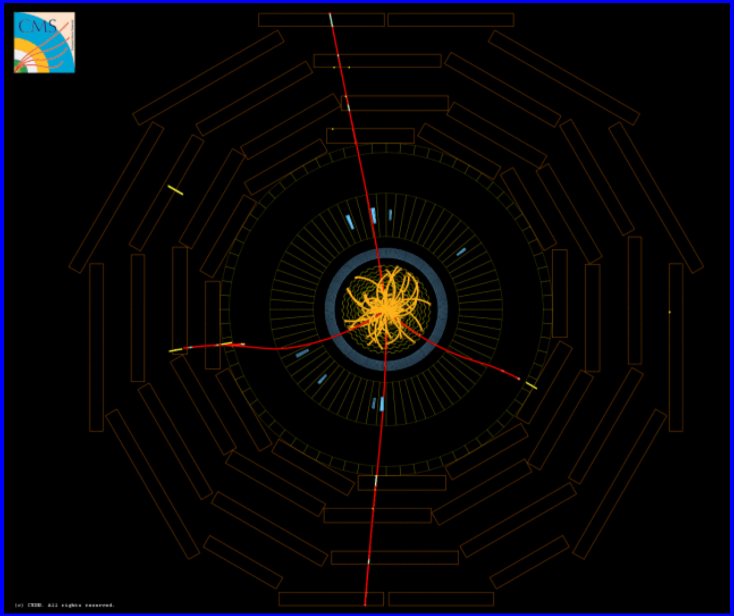
- H-> γγ
- H-> ZZ->μμμμ
- H-> ZZ->eeee
- H->WW
- H->ττ
- H->b bbar



Higgs candidate events

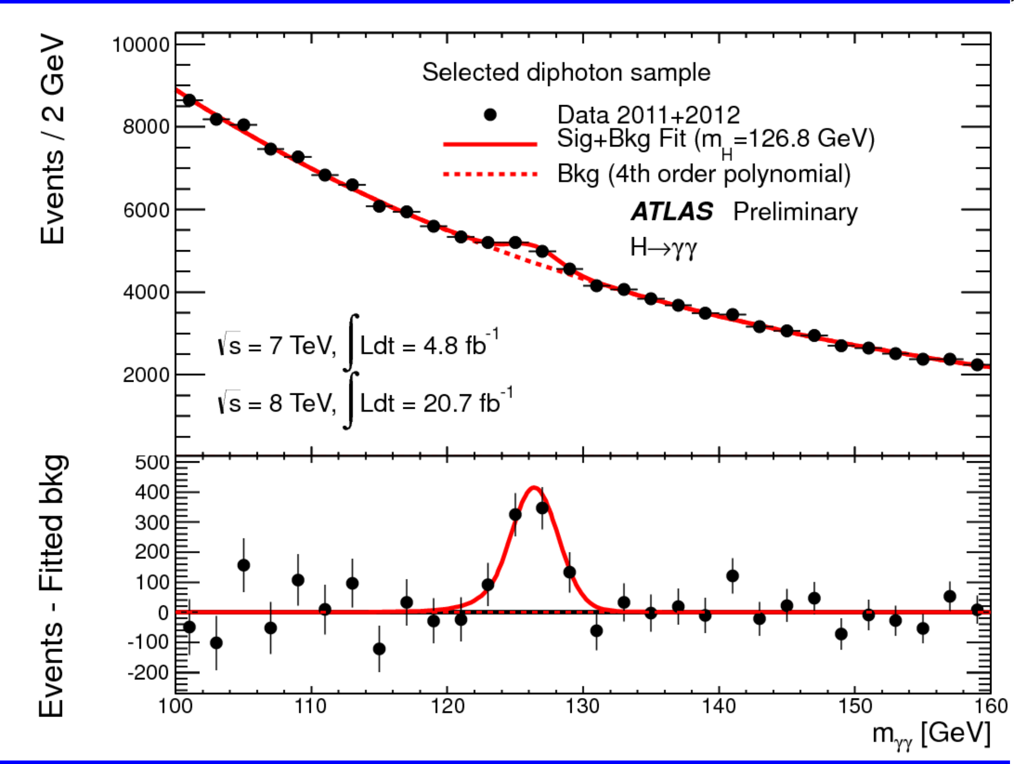


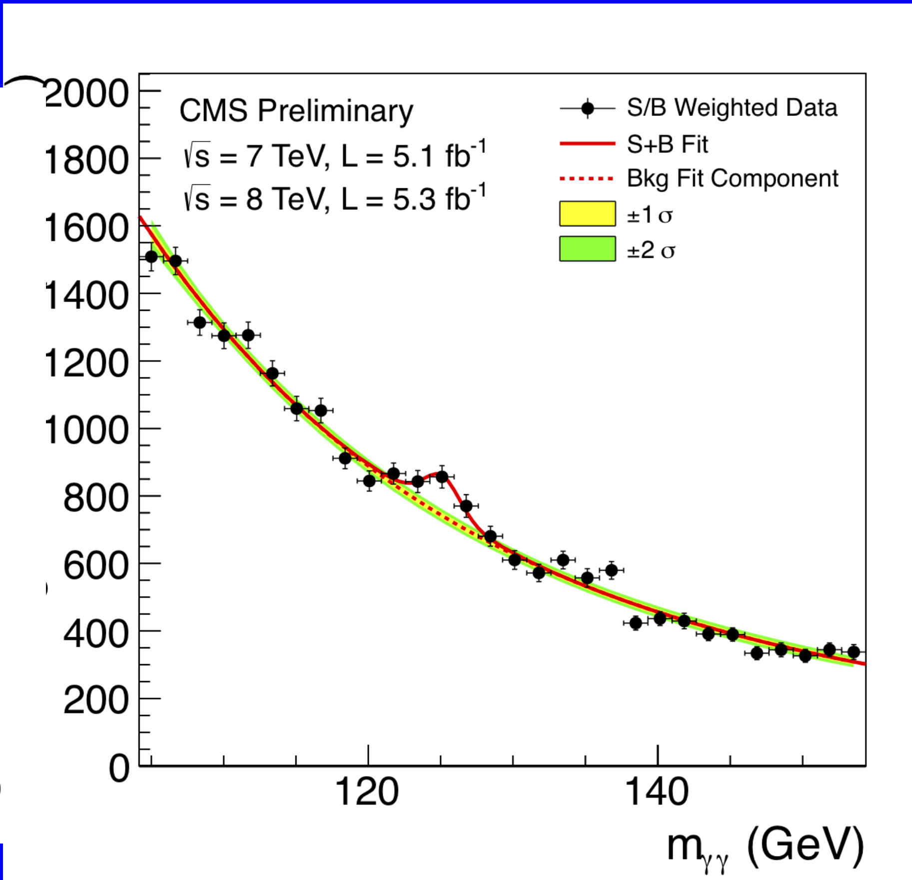
Proton-proton collision with 4 electrons



Proton-proton collision with 4 muons

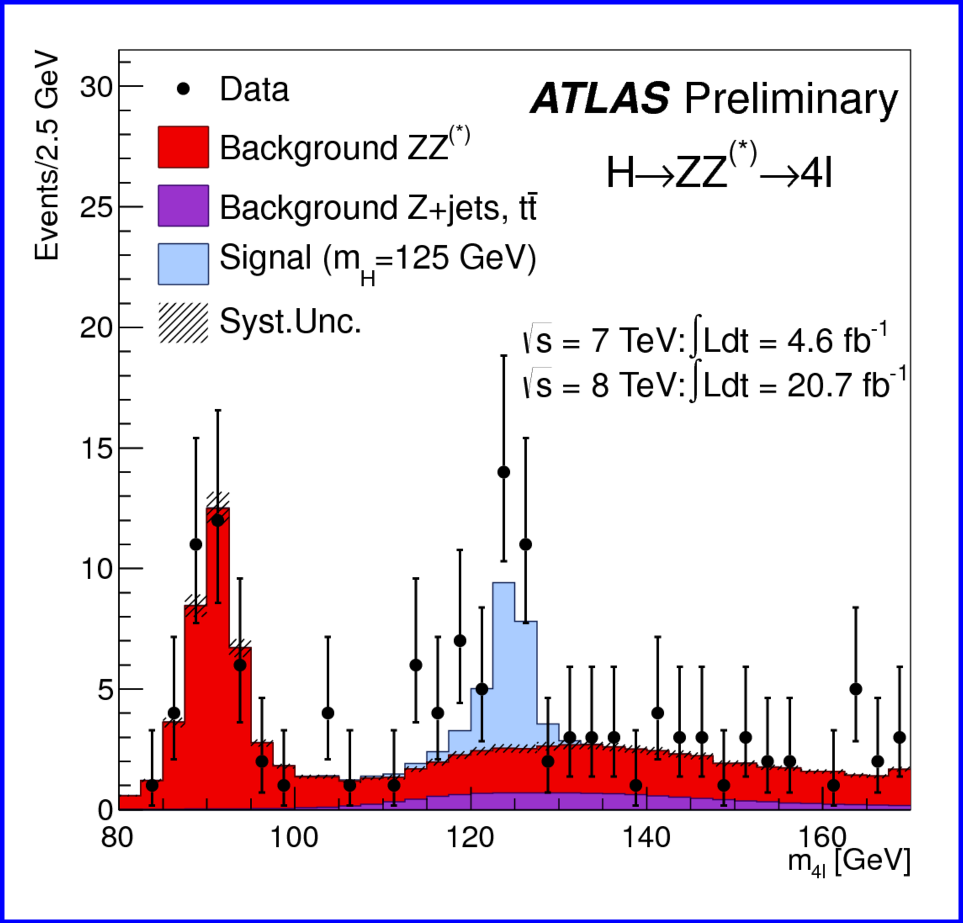
Search for Higgs -> γγ, invariant mass distribution for two-photon candidates

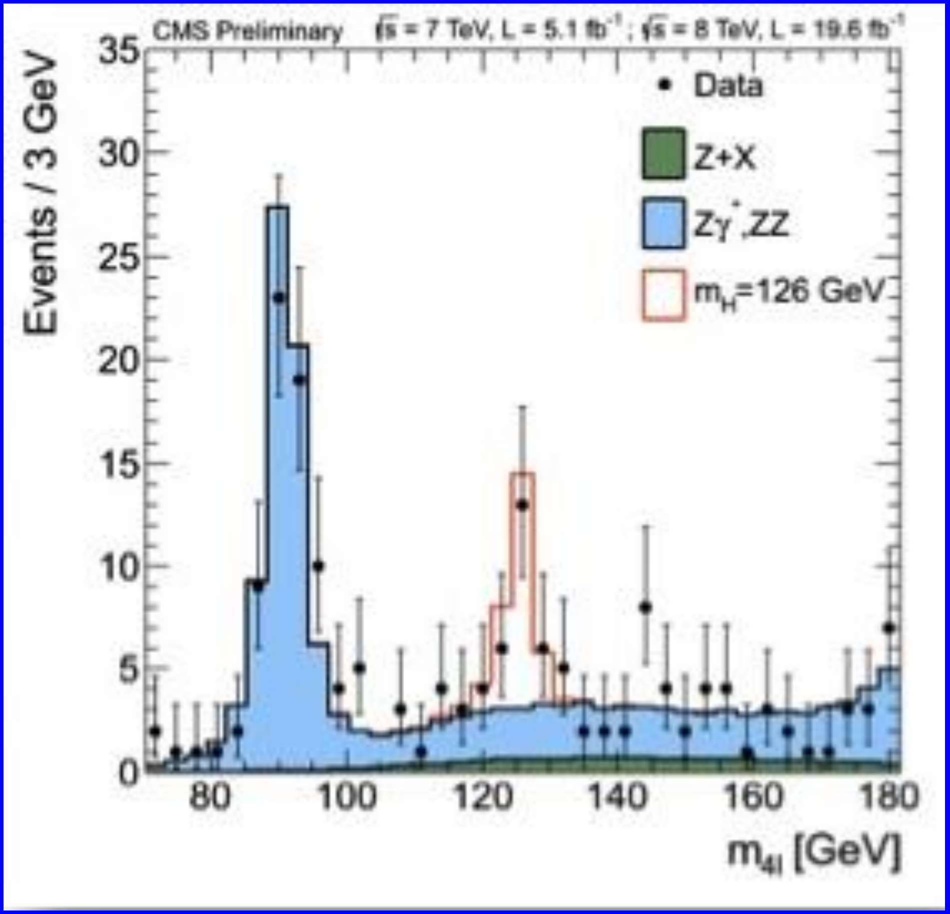




We have to separate the Higgs from the background (continuous line) : random pairs of photons, mainly from π^o and η decays

Search for Higgs -> ZZ-> 4 leptons (electrons or muons)
invariant mass distribution for 4 leptons



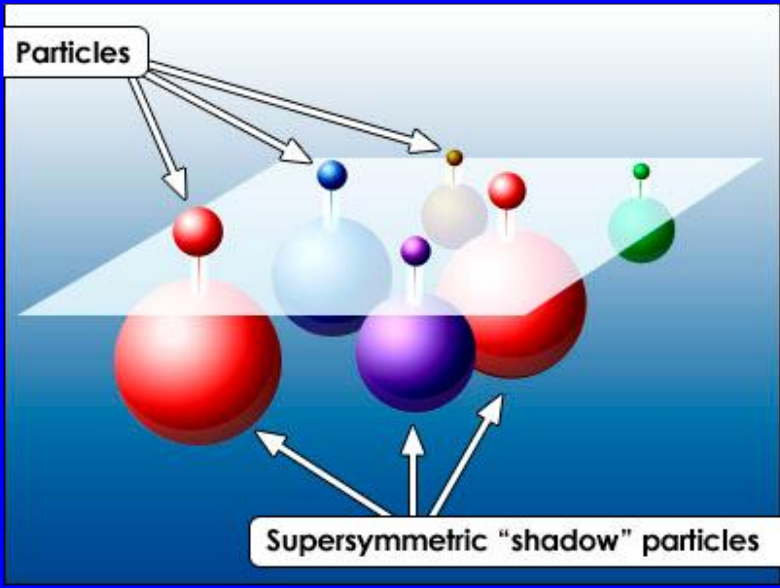


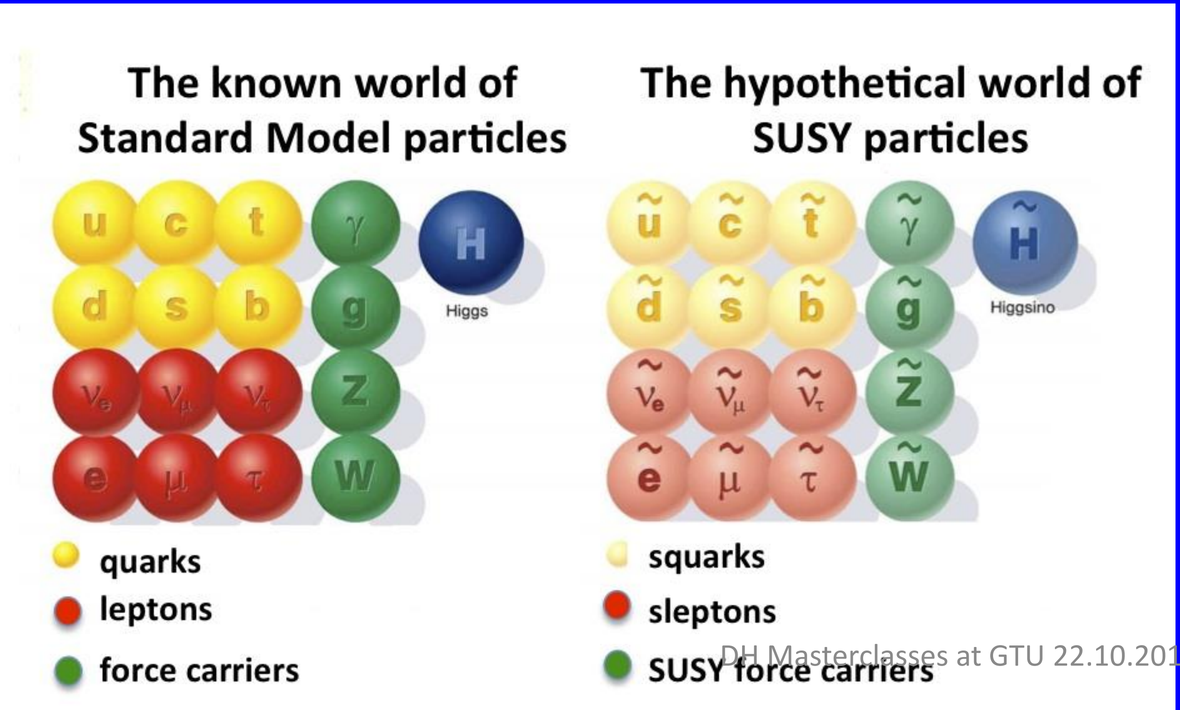
SUperSYmmetry (SUSY)

Symmetry between matter (elementary particles -> fermions) and forces (force carriers -> bosons)

Why is SUSY needed?

To unify the forces
To solve problems in the Standard Model (deviations in the Higgs mass)

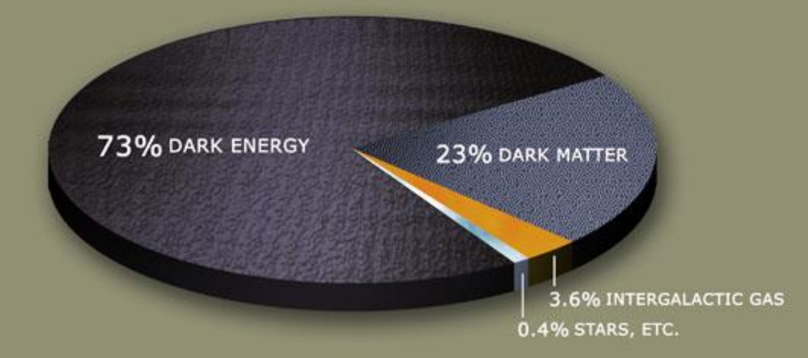




Every particle with spin s has its supersymmetric partner with spin s-1/2

Quark (s=1/2) -> squark (s=0)
Gluon (s=1) -> gluino (s=1/2)

Dark Matter

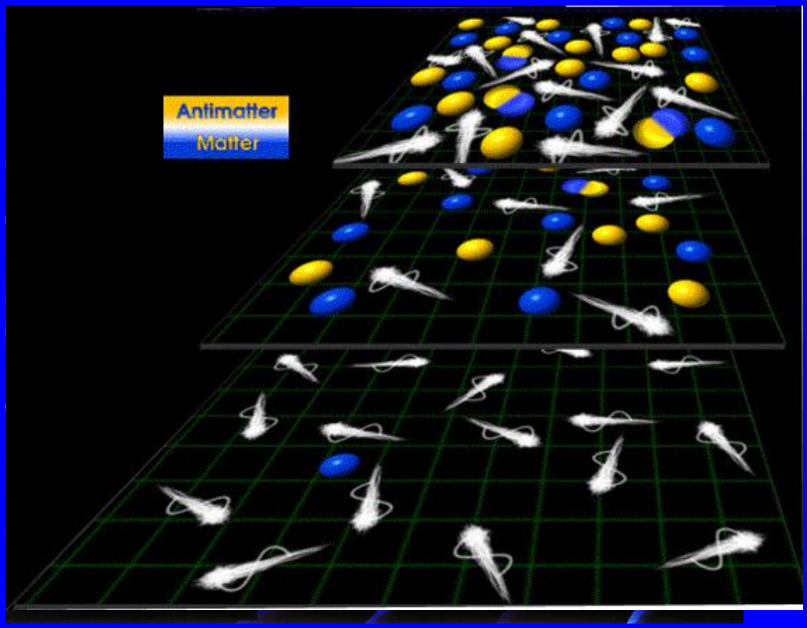


4 % only is the visible matter

Galaxies in our universe are rotating with such speed that the gravity generated by their observable matter could not possibly hold them together; they should have torn themselves apart long ago. The same is true of galaxies in clusters, which leads scientists to believe that something they cannot see is at work. They think something we have yet to detect directly is giving these galaxies extra mass, generating the extra gravity they need to stay intact. They call this mysterious stuff dark matter.

Supersymmetric particles could be the answer

The mystery of antimatter



13,7 billion years ago: Big Bang

Transformation of energy to mass in a gigantic scale

t ~ 0 :

quantity of matter= quantity of antimatter

t ~ 0.001 s :

all antimatter has disappeared

but some matter is left

most energy is photons

Today :

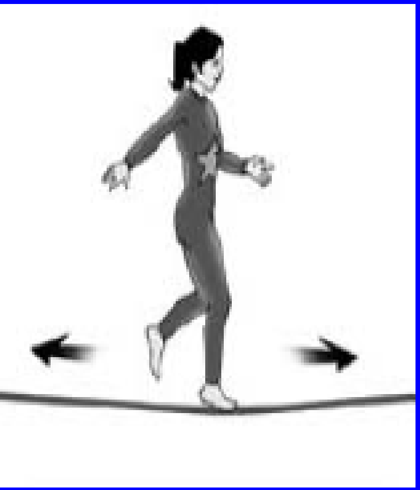
>2,000,000,000 photons for every proton or neutron

Why is our Universe made of matter only?

Is it because matter and antimatter have slightly different properties? (such as mass, charge, ..)

Or is it because they have different decay properties?

Do we live in a world with extra dimensions?



The acrobat is moving in one dimension
The insect is moving in two dimensions, but one of them is very small

Extra dimensions might exist, but they would be so small that we can not perceive them

Evidence of extra dimensions could explain the mystery of gravity : why it it so much weaker than all other forces

Maybe it acts partially in another dimension

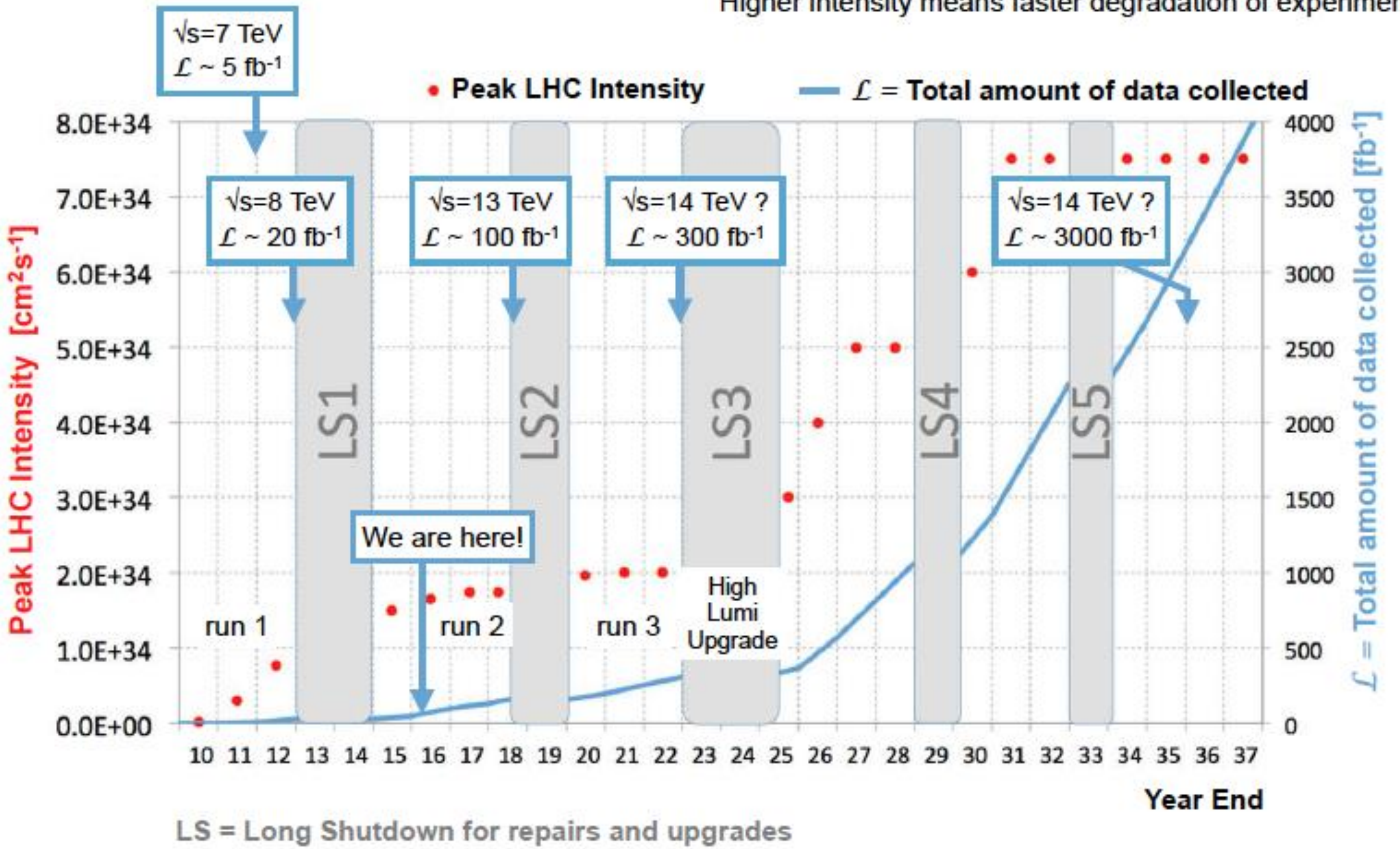
Extra dimensions are also needed by string theory

- Fundamental particles are not like points or dots, but rather small loops of vibrating strings.
- All the different particles and forces are different oscillation modes of a unique type of string.

String theory requires

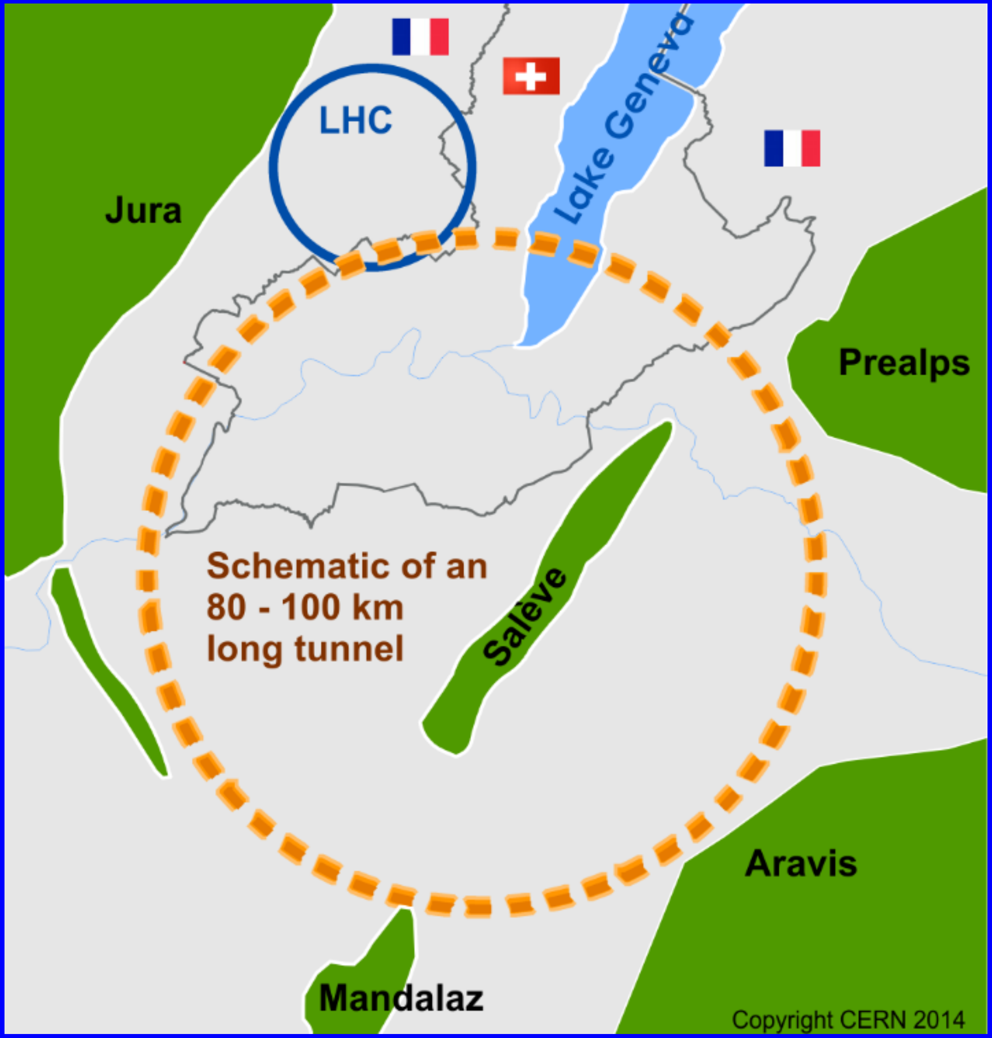
- six additional spatial dimensions!
- these extra dimensions are apparently 'curled up' so small that we do not see them.

Large increases in intensity
Requires significant changes to LHC magnets
Higher intensity means faster degradation of experiments



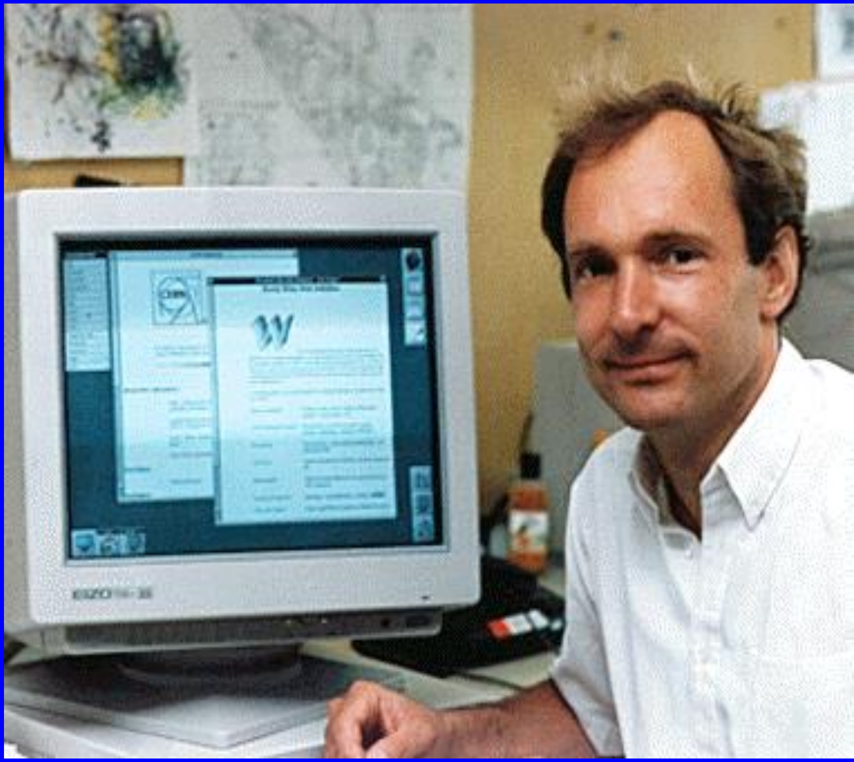
We hope to find answers to some of the unanswered questions..

- .. Future Circular Collider (FCC)



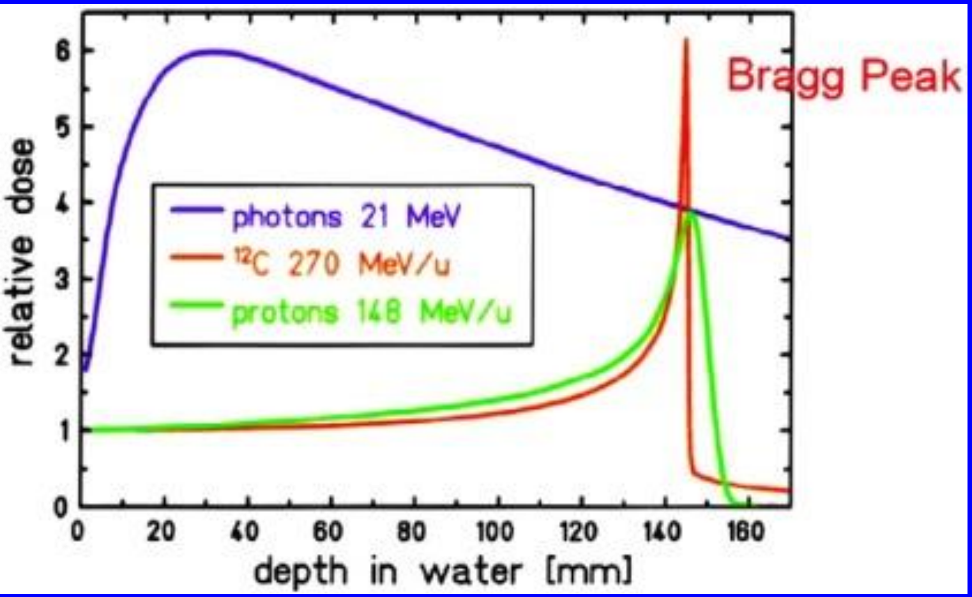
World Wide Web

Invented by Tim Berners-Lee,
Researcher at CERN, in 1989,
In order to satisfy the needs of physicists in Institutes all over the world to share information



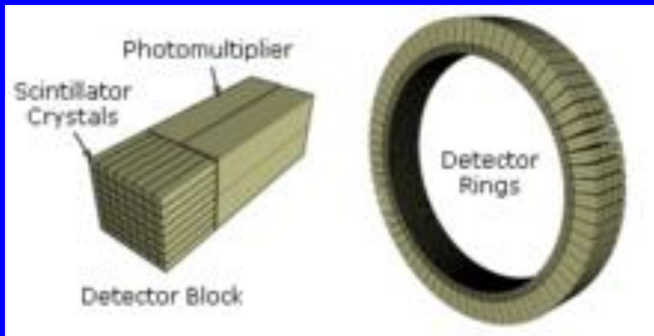
Tthe WWW together with Internet has revolutionized our way of life

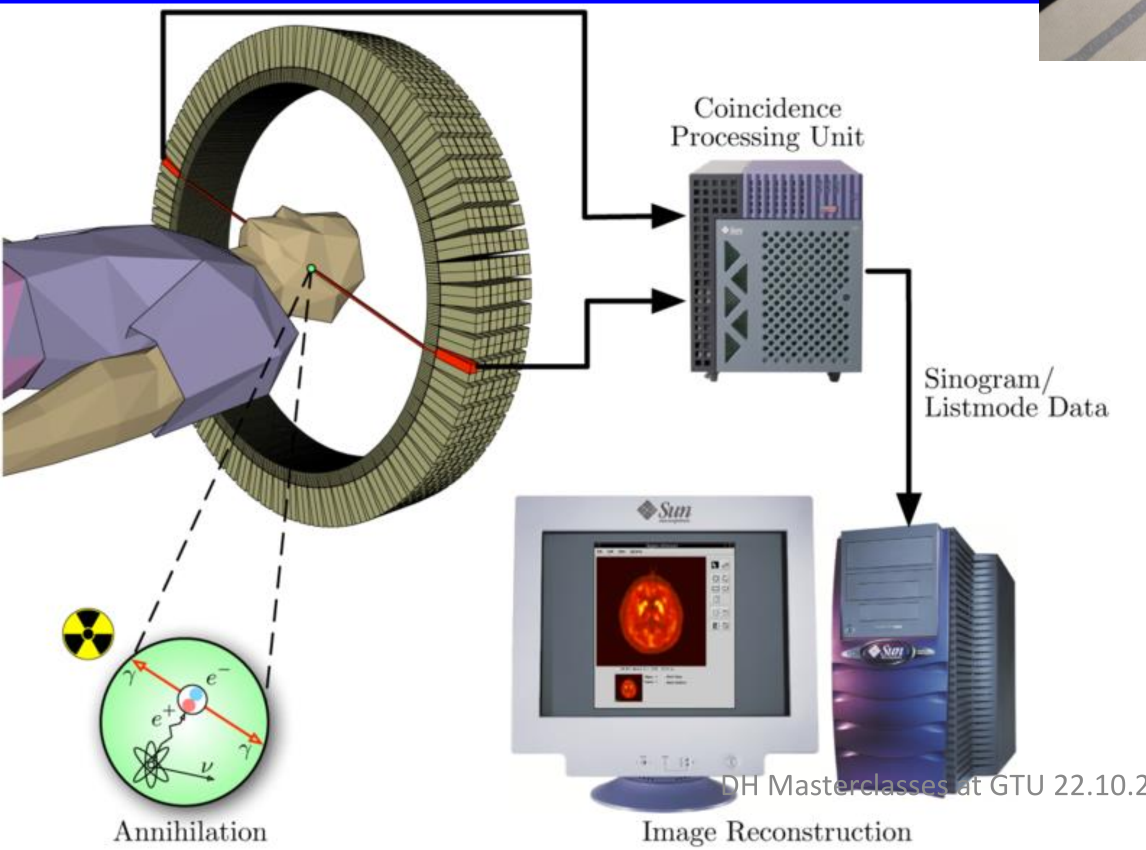
Hadron therapy



Using beams of protons or carbon ions we can adjust the depth where the maximum dose is deposited (by varying the beam energy); in this way we destroy the tumor and not the healthy tissues.

Positron Emission Tomography (PET)





More spin-offs

- High vacuum technology
- Superconductive magnet techology
- Cryogenics
- Fast electronics
- Fast computers

Instead of conclusion

These are very interesting times for the understanding of the Laws of Nature
The answers that LHC will give us, in the next decade, whichever they are

- On the properties of the Higgs-like boson
- On SUperSYmmetry
- On dark matter
- ....

will be essential for shaping the limits of our knowledge

CERN is the instrument for all that
But in addition to broadening the horizons of our scientific knowledge

- It develops new technologies in accelerators and detector
- It trains tomorrow's scientists and engineers
- It unites people from different cultures from all over the world, who work together in a common endeavour