The CERN Large Hadron Collider
at the frontier of knowledge and technology

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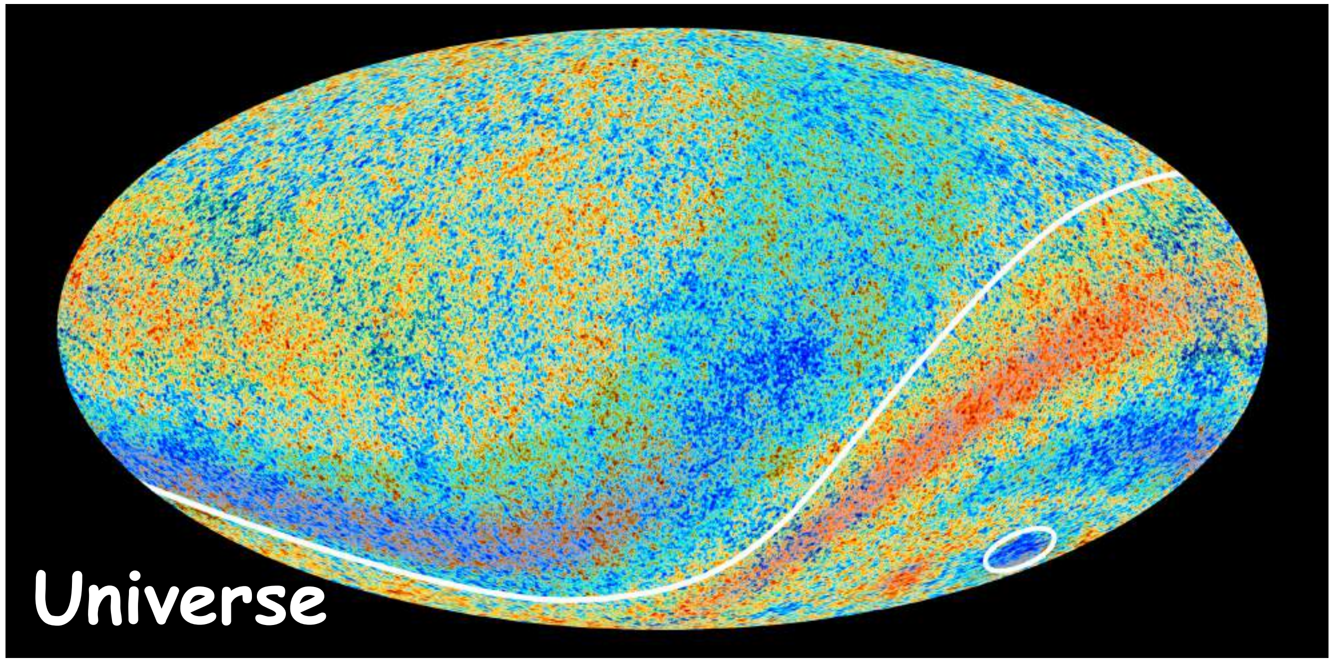
INSPYRE 2016

Fundamental research at LHC



Which are the fundamental blocks of the matter?

Which are the forces?

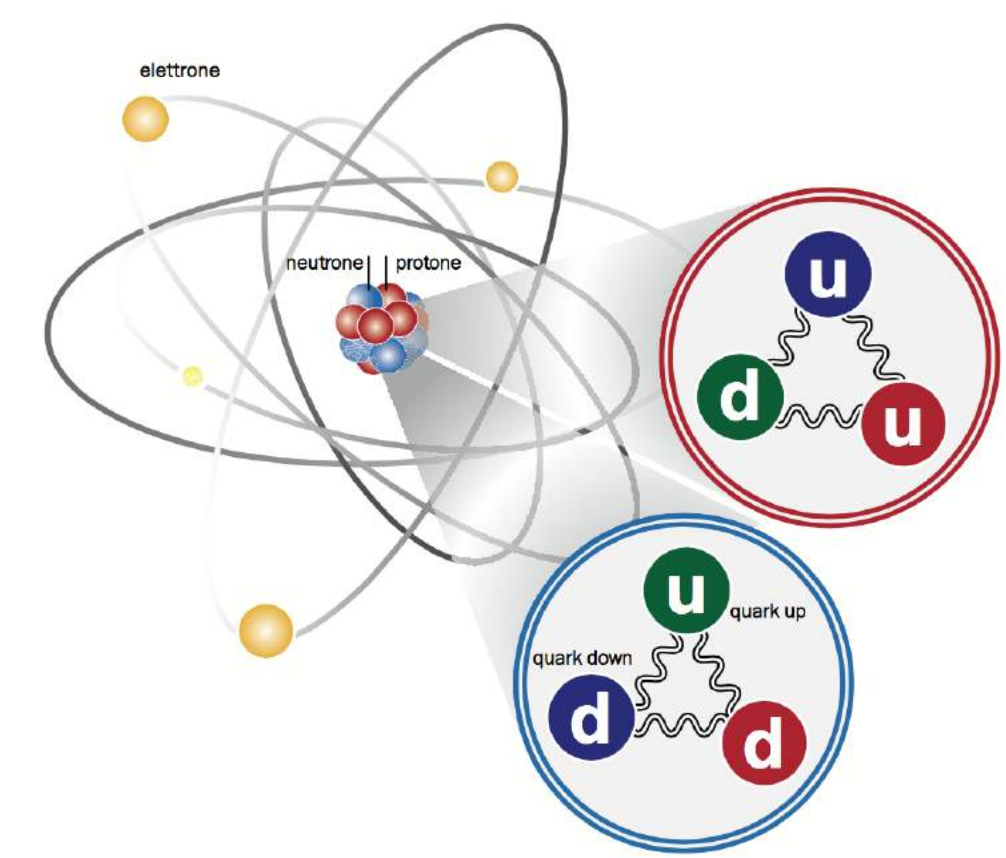
How matter and forces determine the properties of the Universe?

How the Universe evolved?

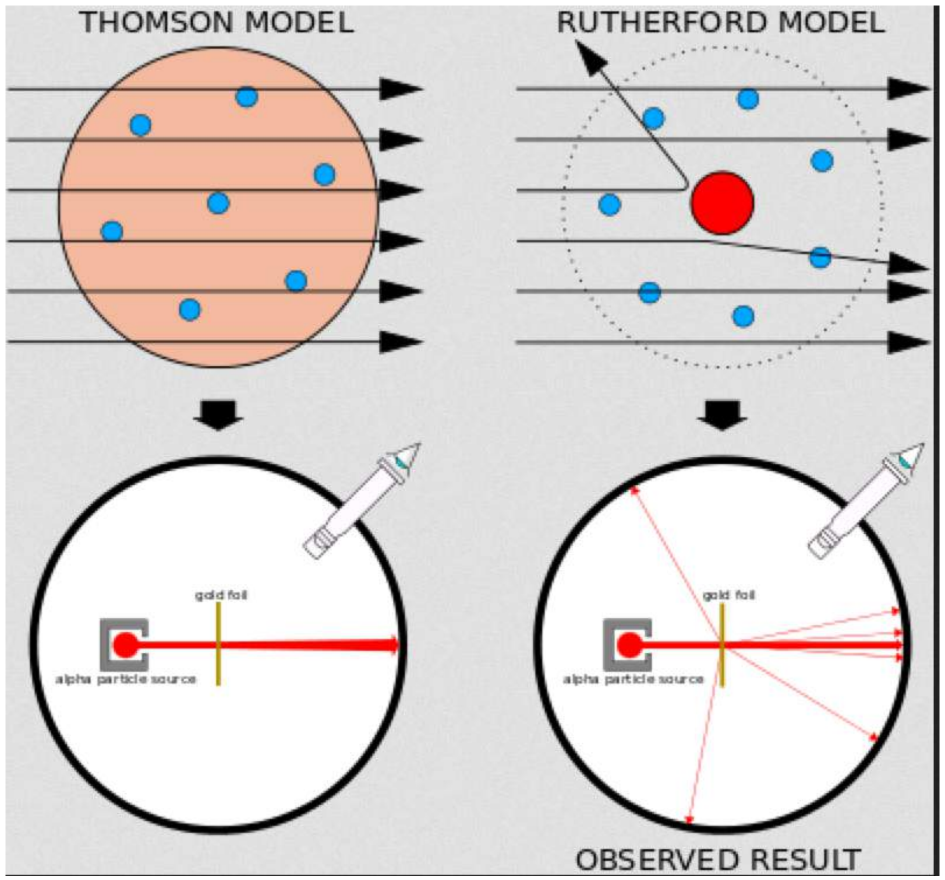
We study the matter constituents

All we know about the **elementary constituents of the matter** and their interactions has been understood by **scattering*** experiment

Credits: Asimmetrie



THE ATOMIC STRUCTURE:
positive nucleus + electron cloud



Geiger and Marsden, 1908

***scattering** = particle projectiles on a target material

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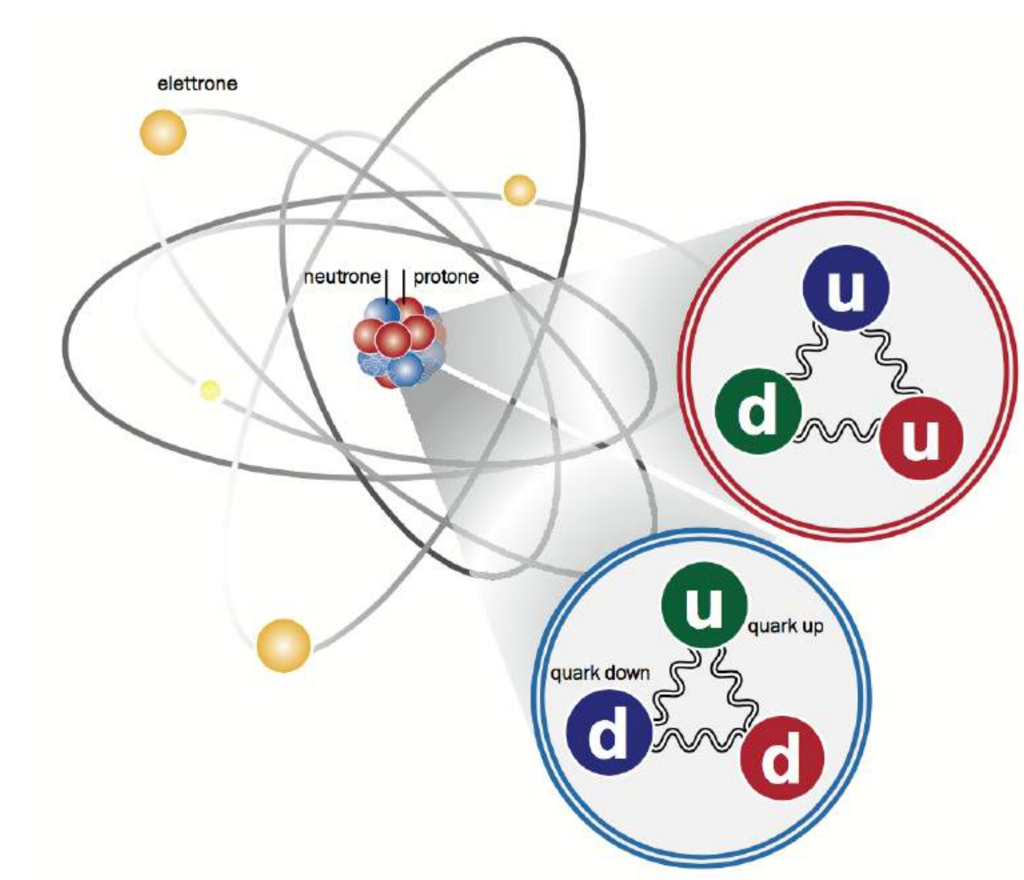
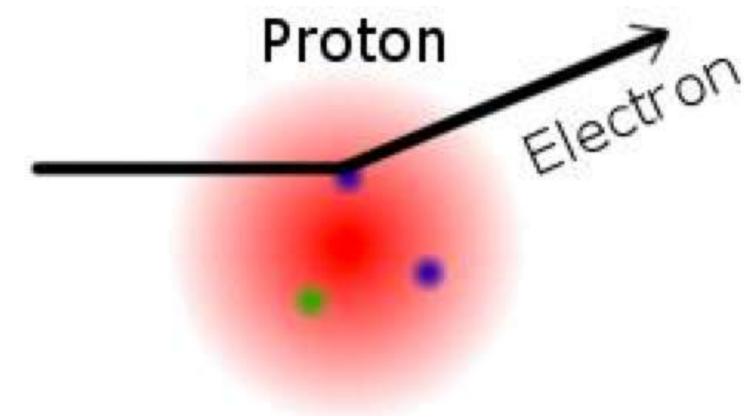


PROTON IS MADE OF QUARKS

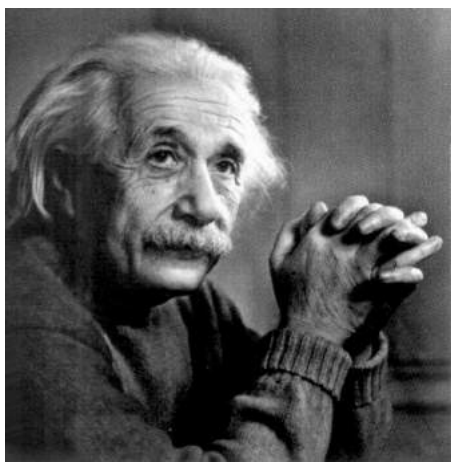


SLAC, 1970s

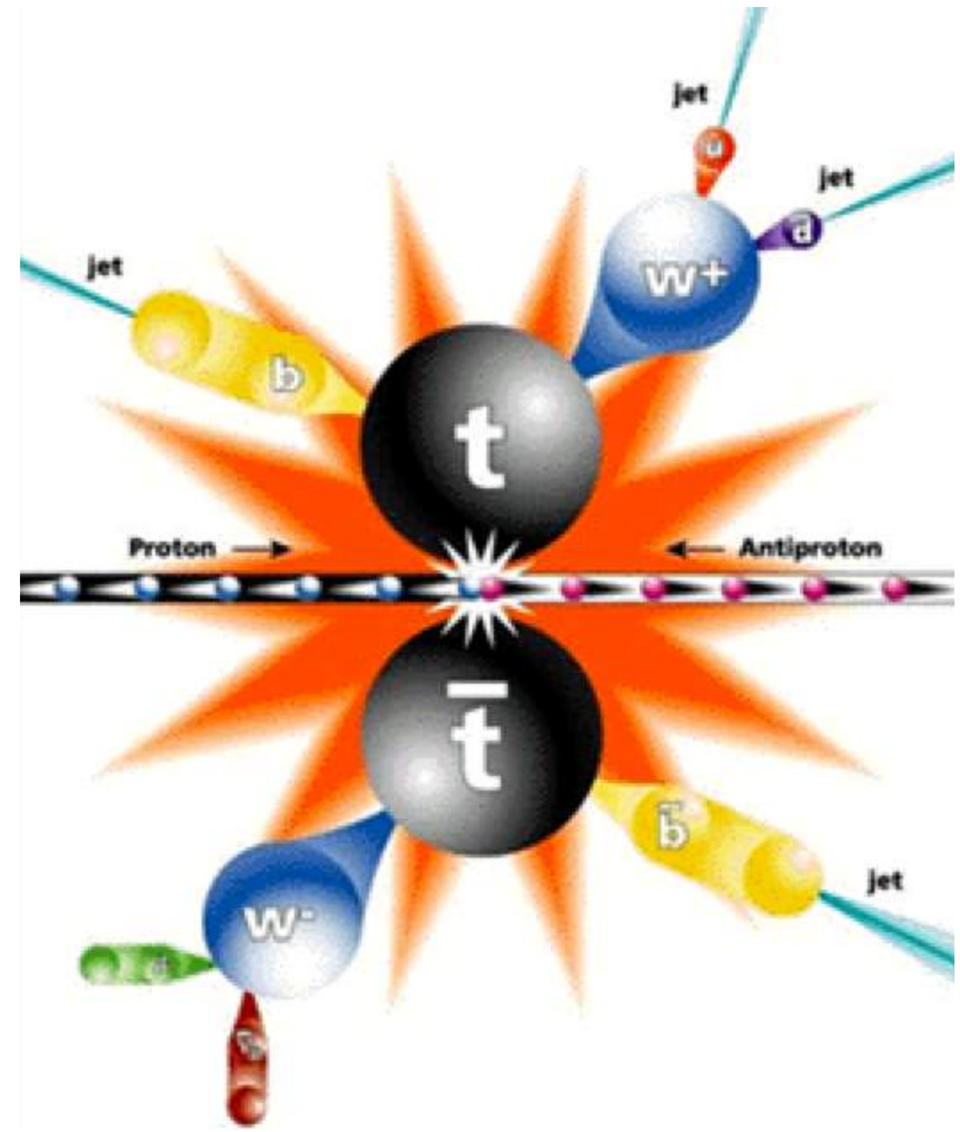
- ✦ Energy units for today: 1eV = 1V x electron charge => 1 MeV = 10^6 eV; 1 GeV = 10^9 eV; 1TeV = 10^{12} eV
- ✦ The more is the particle projectile **energy** E, the more is the **spatial resolution** d with which we explore the matter: e.g. E=200 MeV -> d=10^{-15} m (= nucleus dimension)

We study the matter constituents

Since 1959 we use a more efficient approach, proposed for the first time in Frascati by Bruno Touschek: **collisions of two opposite momentum particles**



In this way, the full kinetic energy of the projectiles is available to create **new** massive objects, according to the **Einstein** law, which for 2 colliding particles of mass **m** read:



$$E_{tot} = 2(m^2 c^4 + p^2c^2)^{1/2} = Mc^2$$

two colliding particles, highly energetic

a new massive object is created, eventually at rest

(With a projectile particle on a fixed target, $M_n c^2$ scales "only" as $\sqrt{p}$)

Many new heavier matter states have been discovered in this way, and we have now a rather complete picture => **the Standard Model**

The Standard Model

Glashow, Weinberg, Salam '67

MATTER

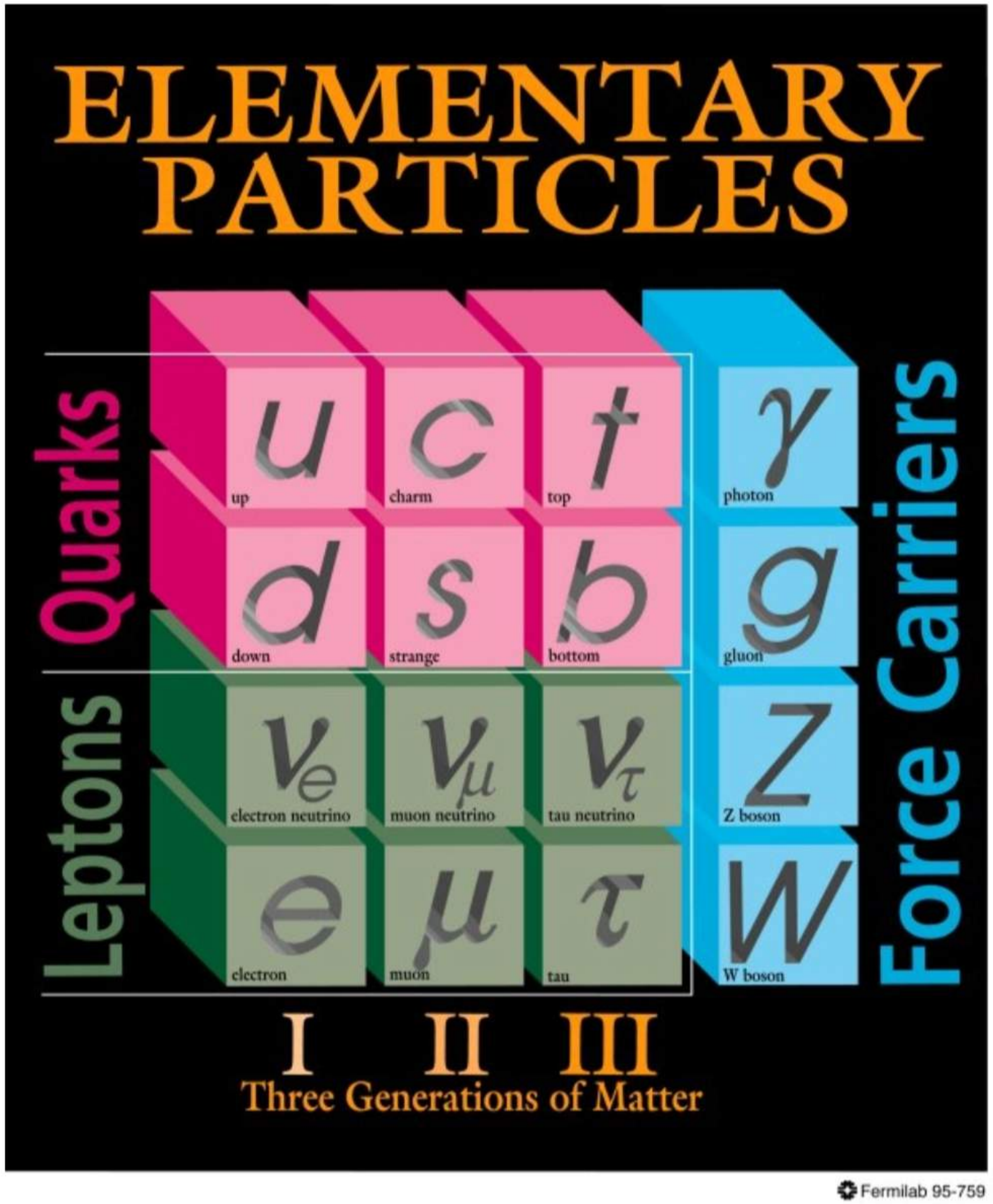
quarks & leptons

- all the forms of matter we observe around us are composed by the elements of 1st generation : up & down quarks, electron & electron neutrino

- 2nd and 3rd generations are identical copies, expect for the higher masses: produced in the cosmic rays, in the sun, **at the particle accelerators**

- **anti-matter exists** (Dirac '28): for each particle, a corresponding anti-particles exists, with same mass, and opposite electric charge:

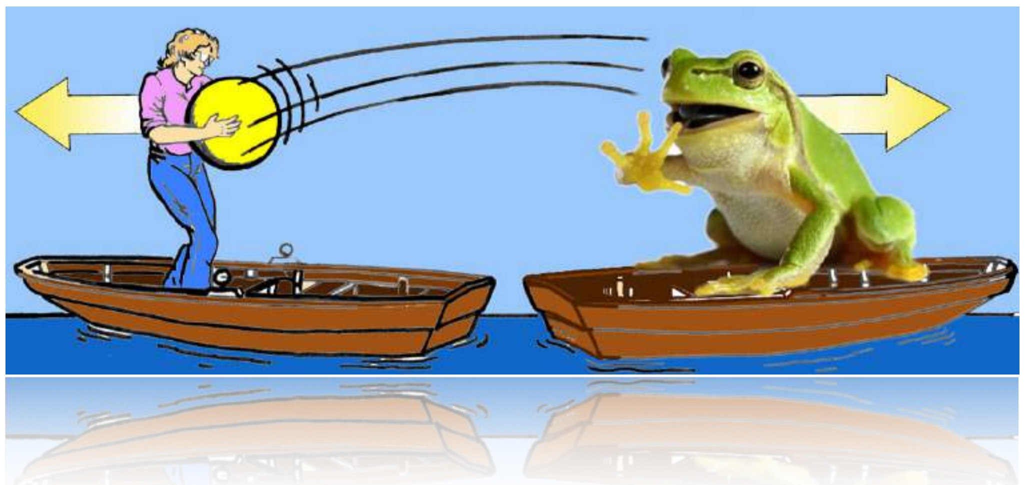
electron e^-
positron e^+



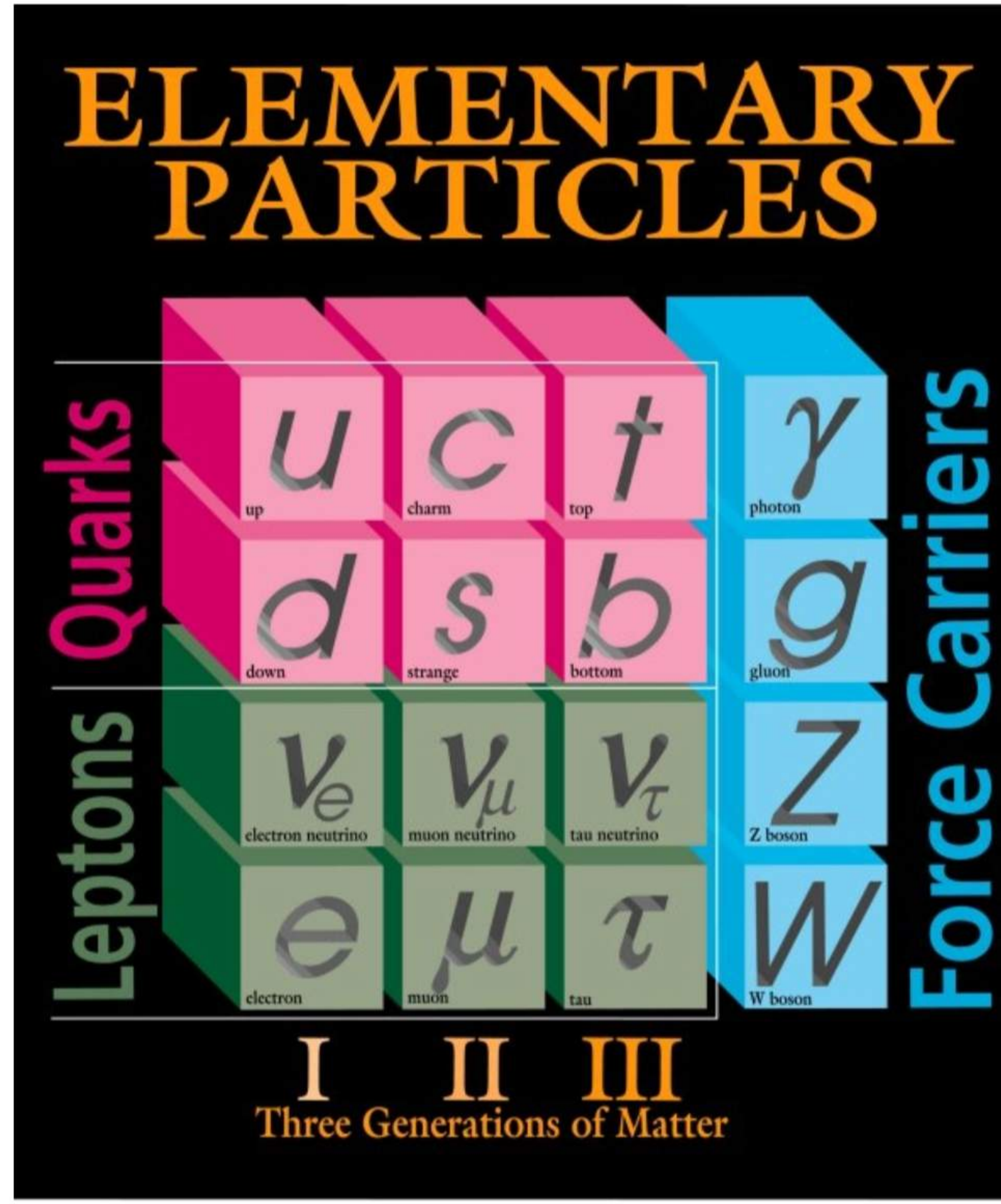
The Standard Model

Glashow, Weinberg, Salam '67

FORCE CARRIERS



- γ : **electromagnetic**, felt by electric charges — strength = 1/137
- **g: strong**, binds the nuclei — strength = 0.4
- **Z and W: weak**, radioactive decays, fusion process in the sun — strength = 10^{-5}
- The strengths become much more similar at higher energies => **force unification**



Fermilab 95-759

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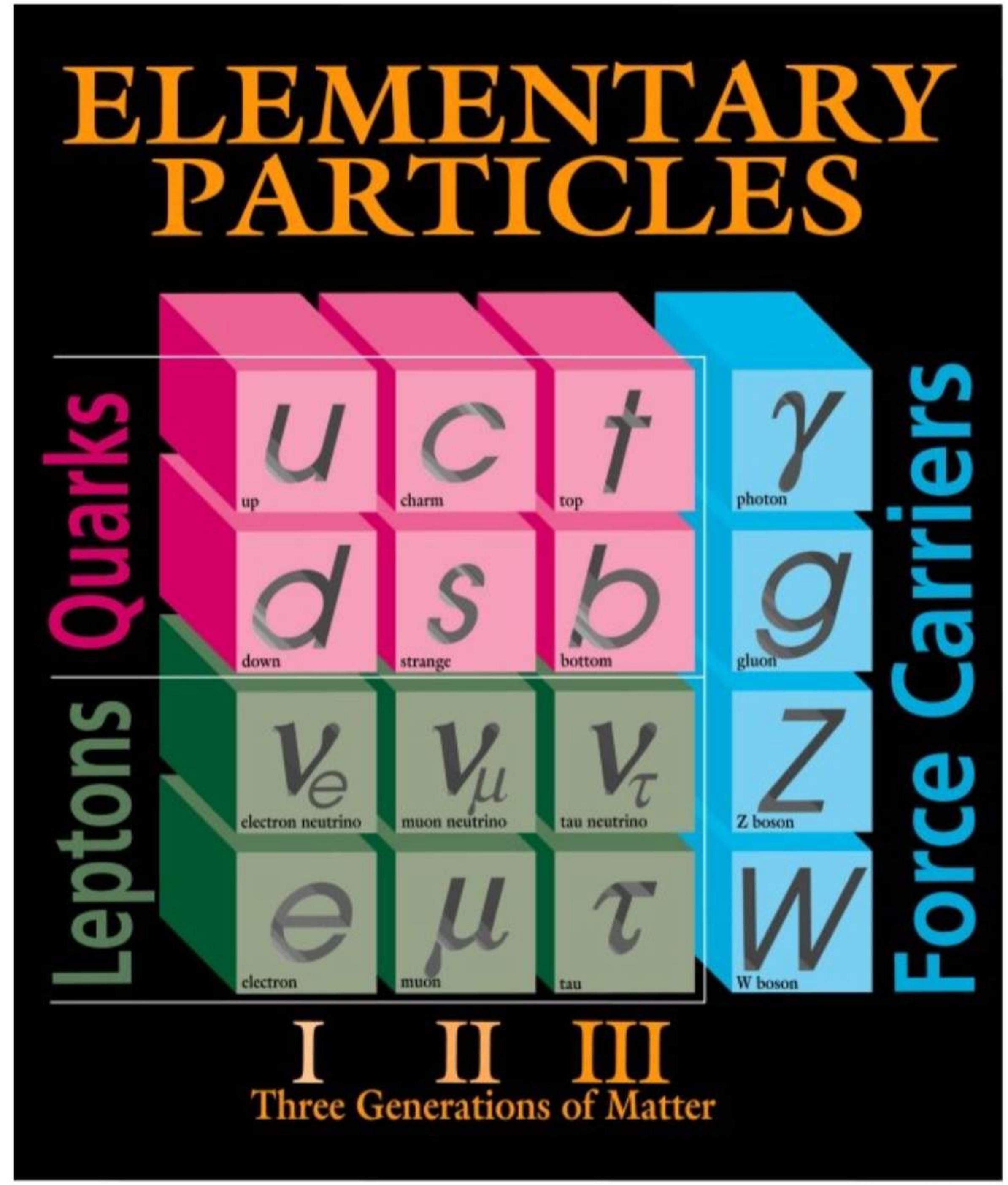
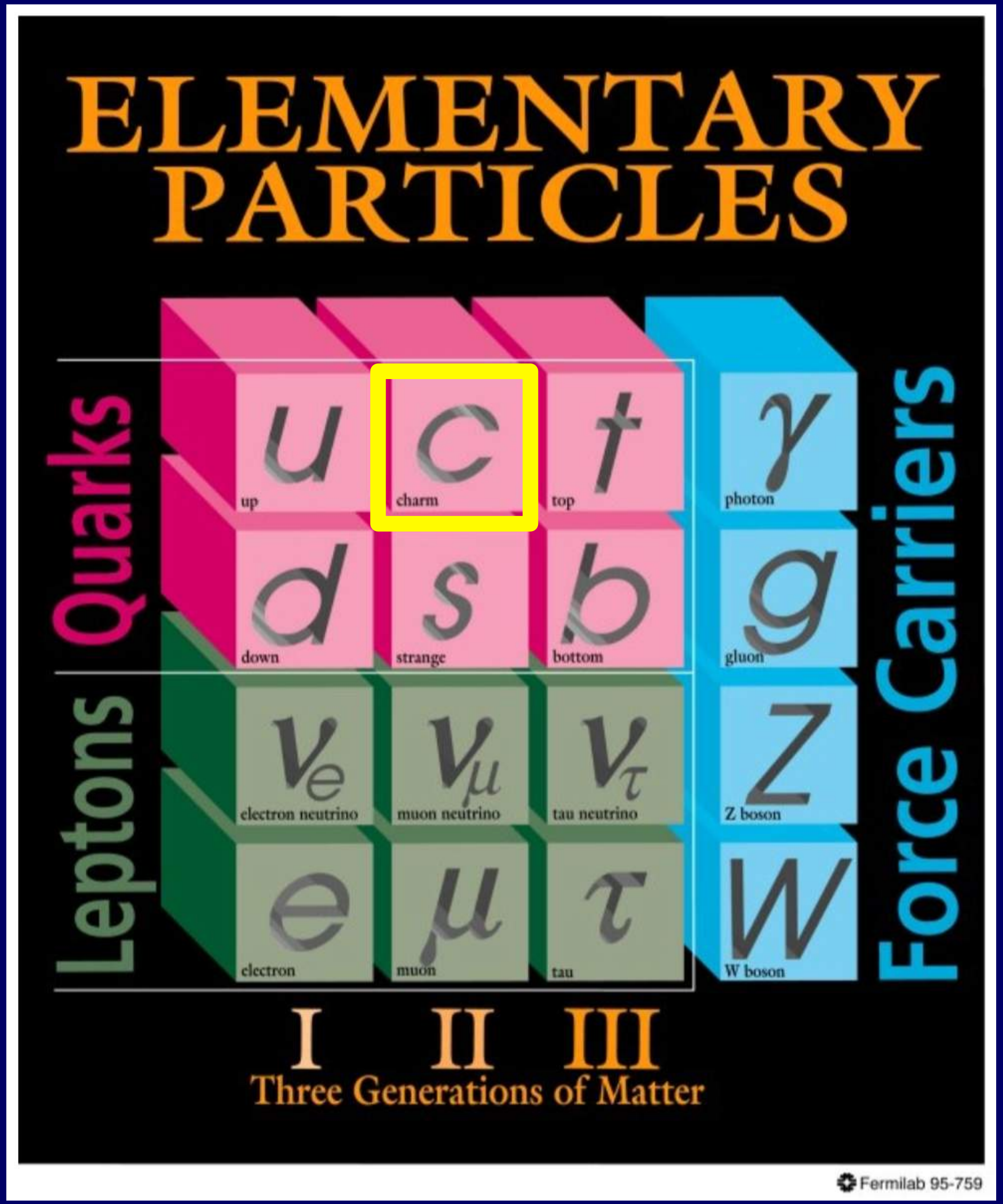


Fermilab 95-759

The last 40 years represent an extraordinary ride to discover all of the pieces of the above puzzle (many Nobel prizes!!)

1974: the c quark discovery

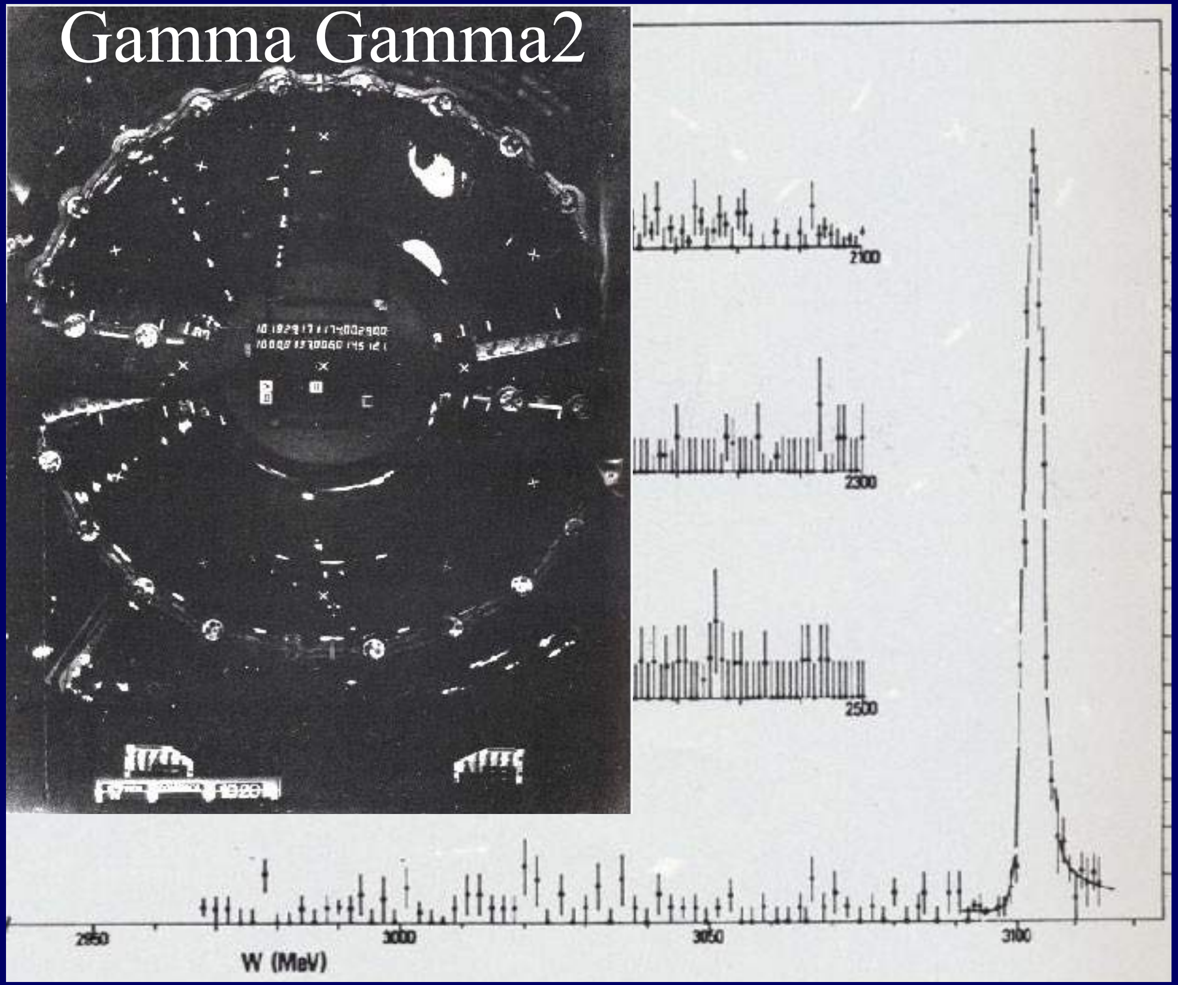
(BNL and SLAC, USA)



c quark mass = 1.5 GeV

(proton mass = 0.94 GeV)

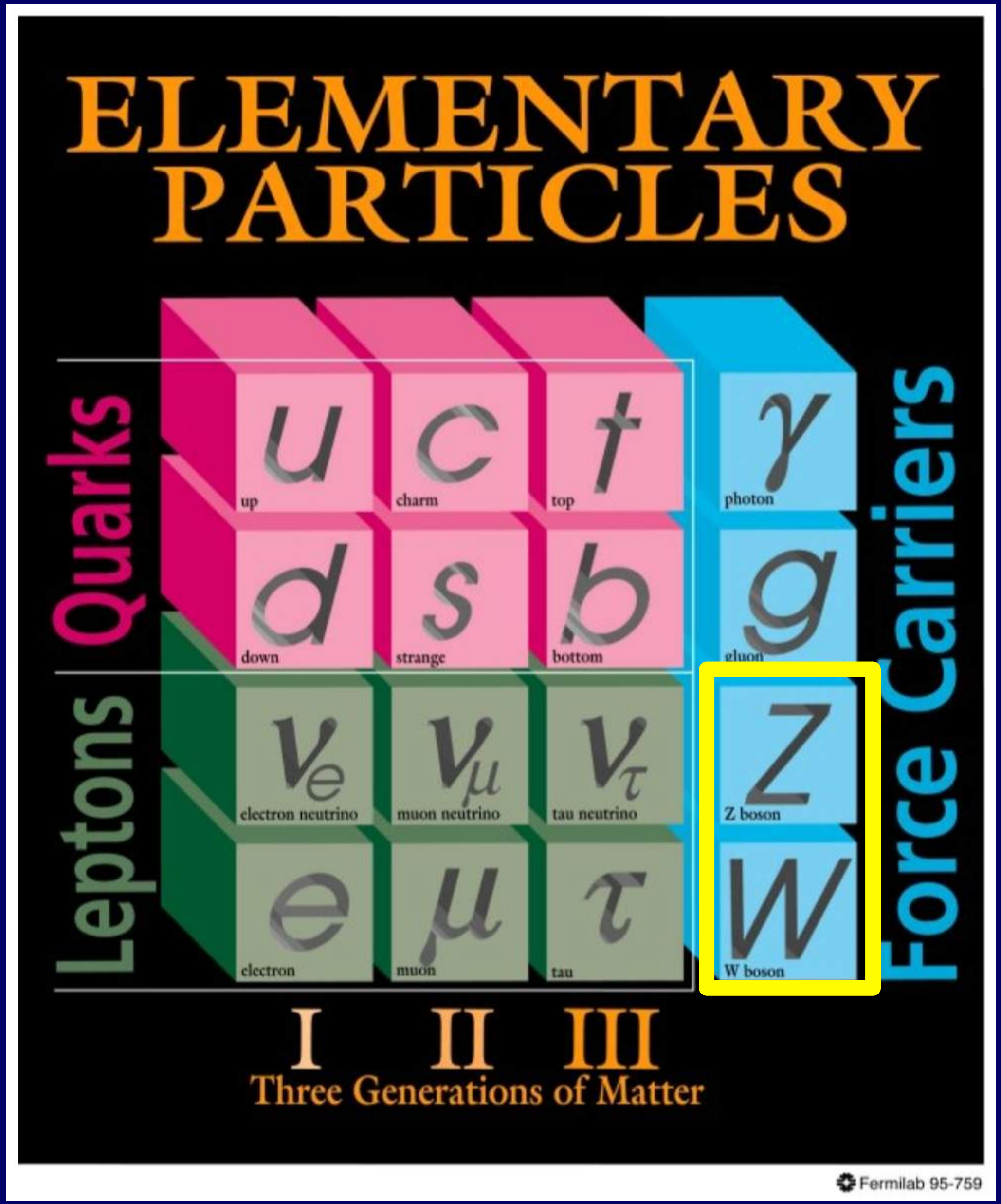
Adone, Frascati 1974



The J/psi particle, containing a couple of quarks c, is visible as a huge peak for an accelerator energy of 3.1 GeV, corresponding to its mass

1984: discovery of W, Z bosons

(CERN)



UA1 experiment at proton-antiproton collider of CERN, Geneva

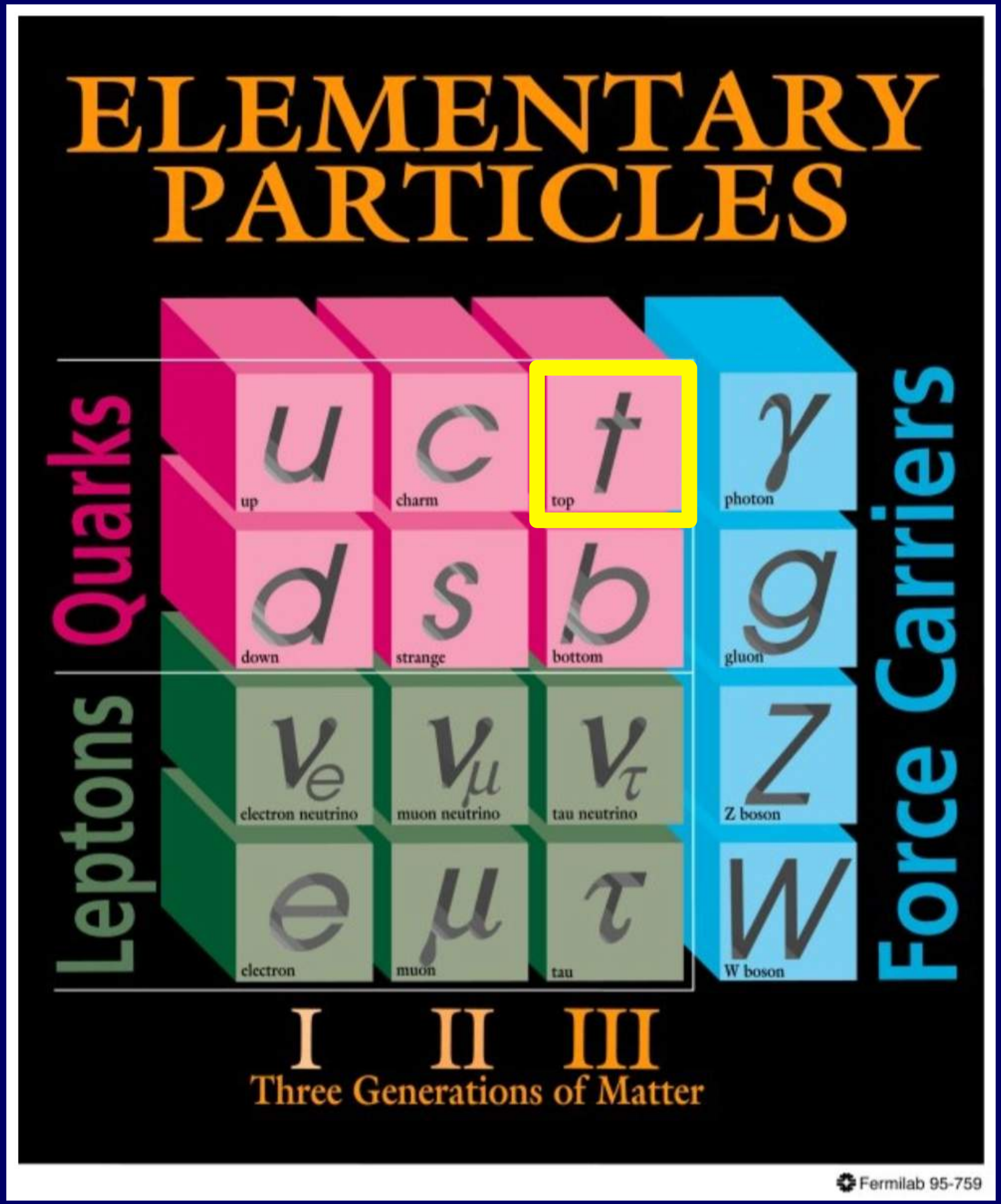
Rubbia, van der Meer (1984)

W boson mass = 80.4 GeV

Z boson mass = 91.2 GeV

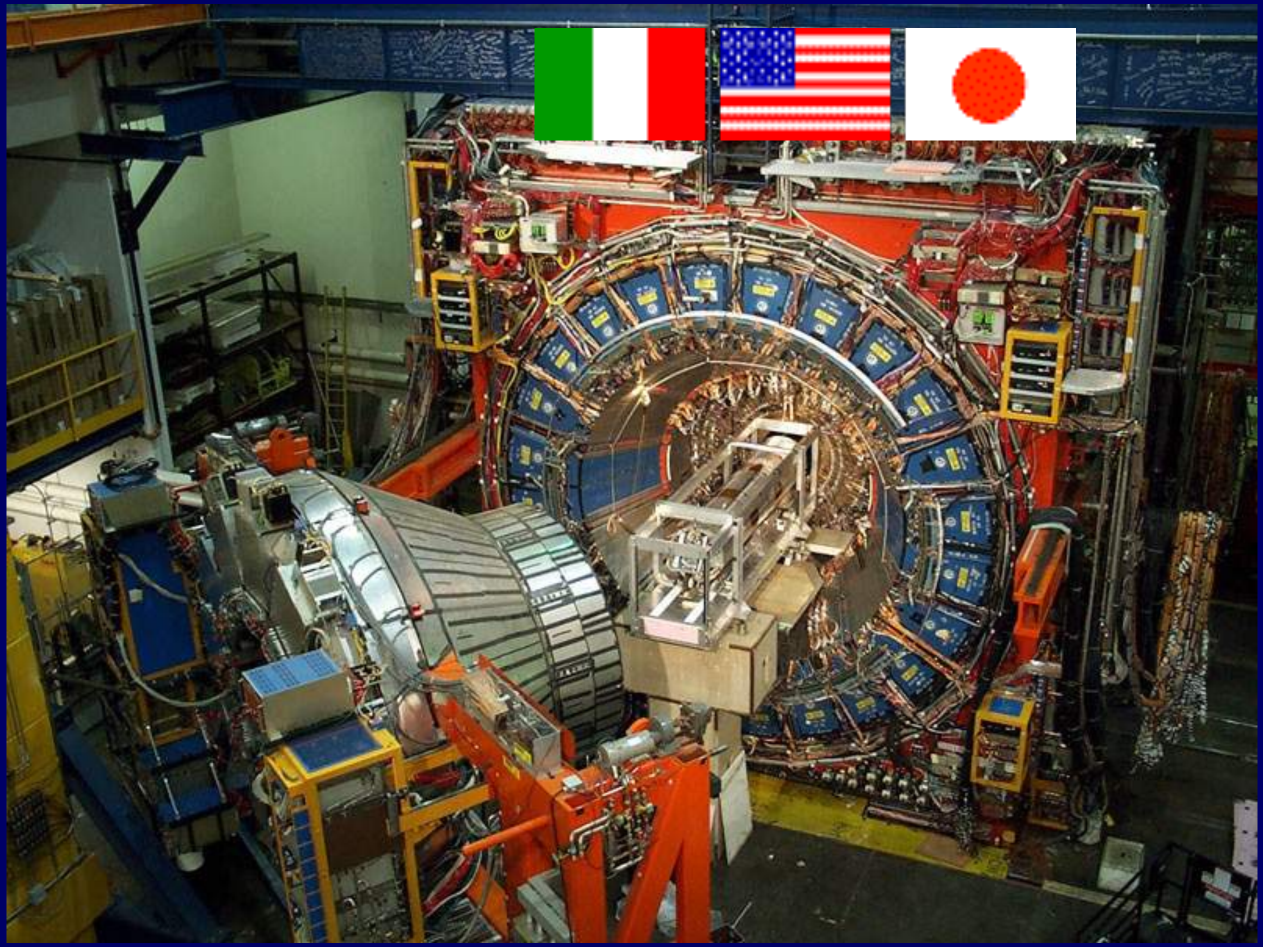
1995: t quark discovery

(Fermilab, USA)



CDF experiment at Tevatron collider of Fermilab (Chicago, 1995)

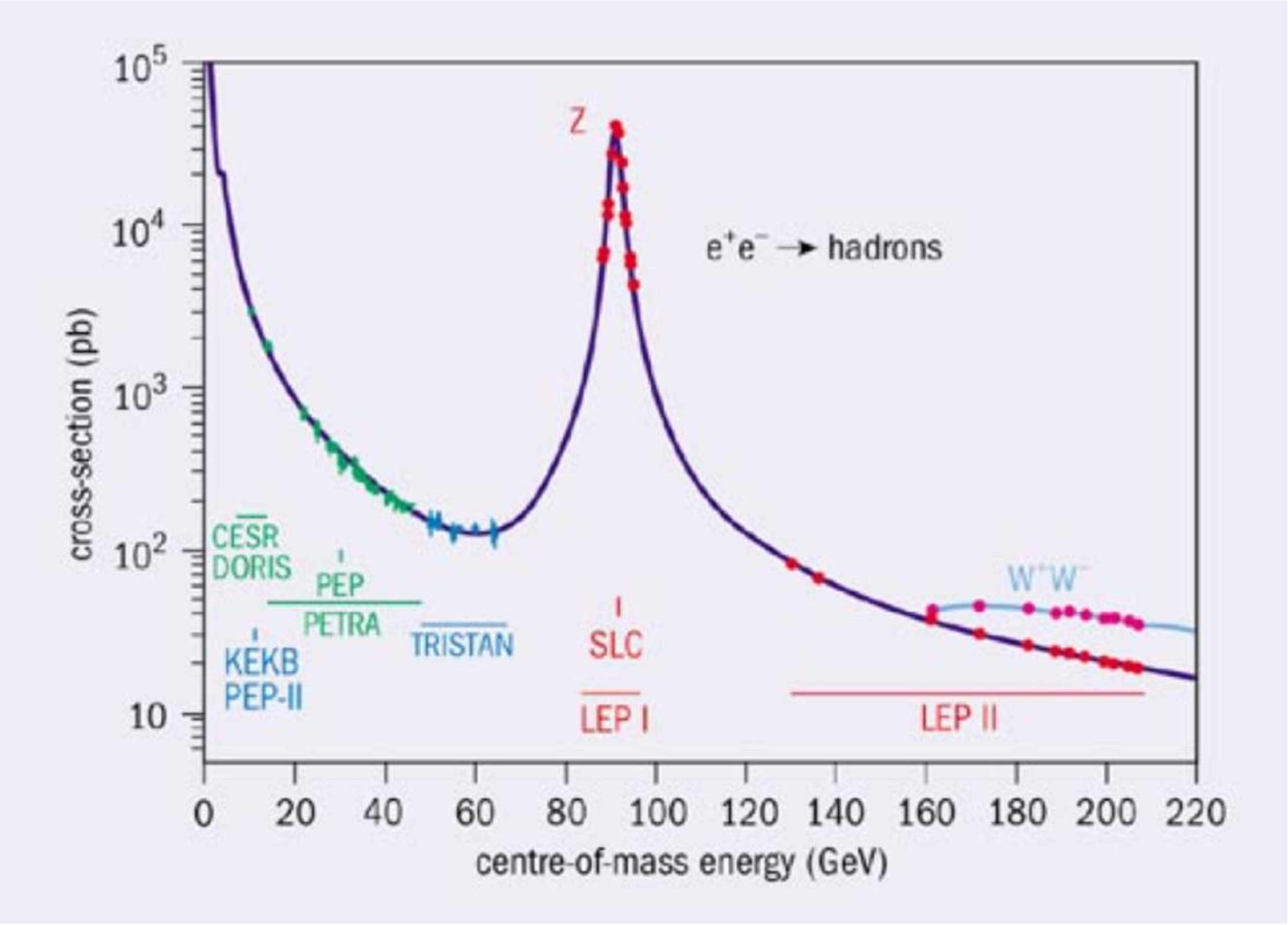
[Etot = 1.8 TeV]



t quark mass = 175 GeV the heaviest!

The power of the Standard Model…

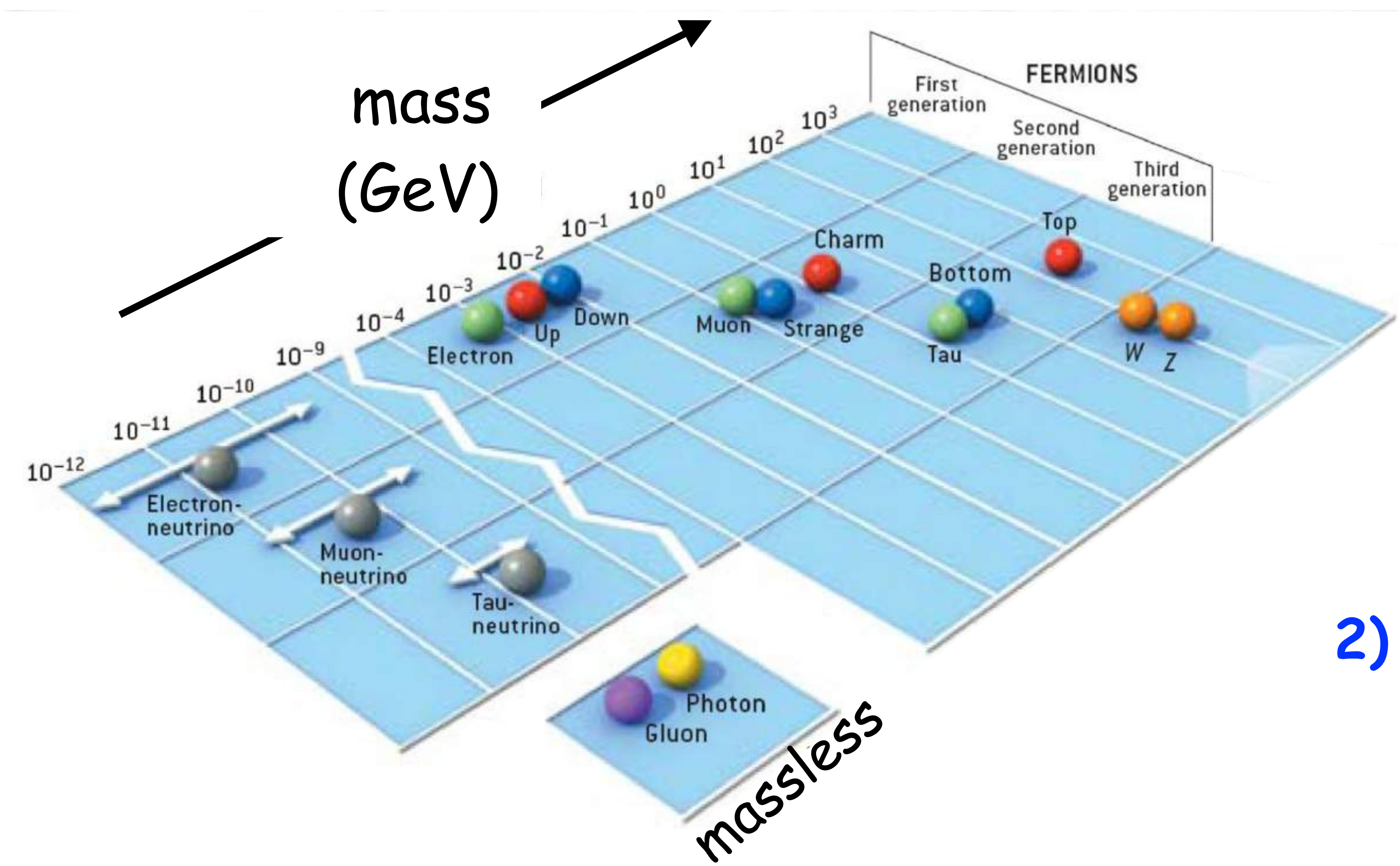
The probability is shown to produce **hadrons (=particles made by quarks, e.g. protons, pions, kaons, etc…)**, when colliding a beam of electrons against a beam of **positrons (= electrons with positive charge)**



The continuous line is the Standard Model prediction, points are measured values: the agreement is incredibly good over a wide energy range

…with a big problem: where's the mass?

The theoretical foundation of the Standard Model implies that none of the particles (lepton, quarks and force carriers) can have a mass: **this is in sharp contradiction to what we find in the experiments**



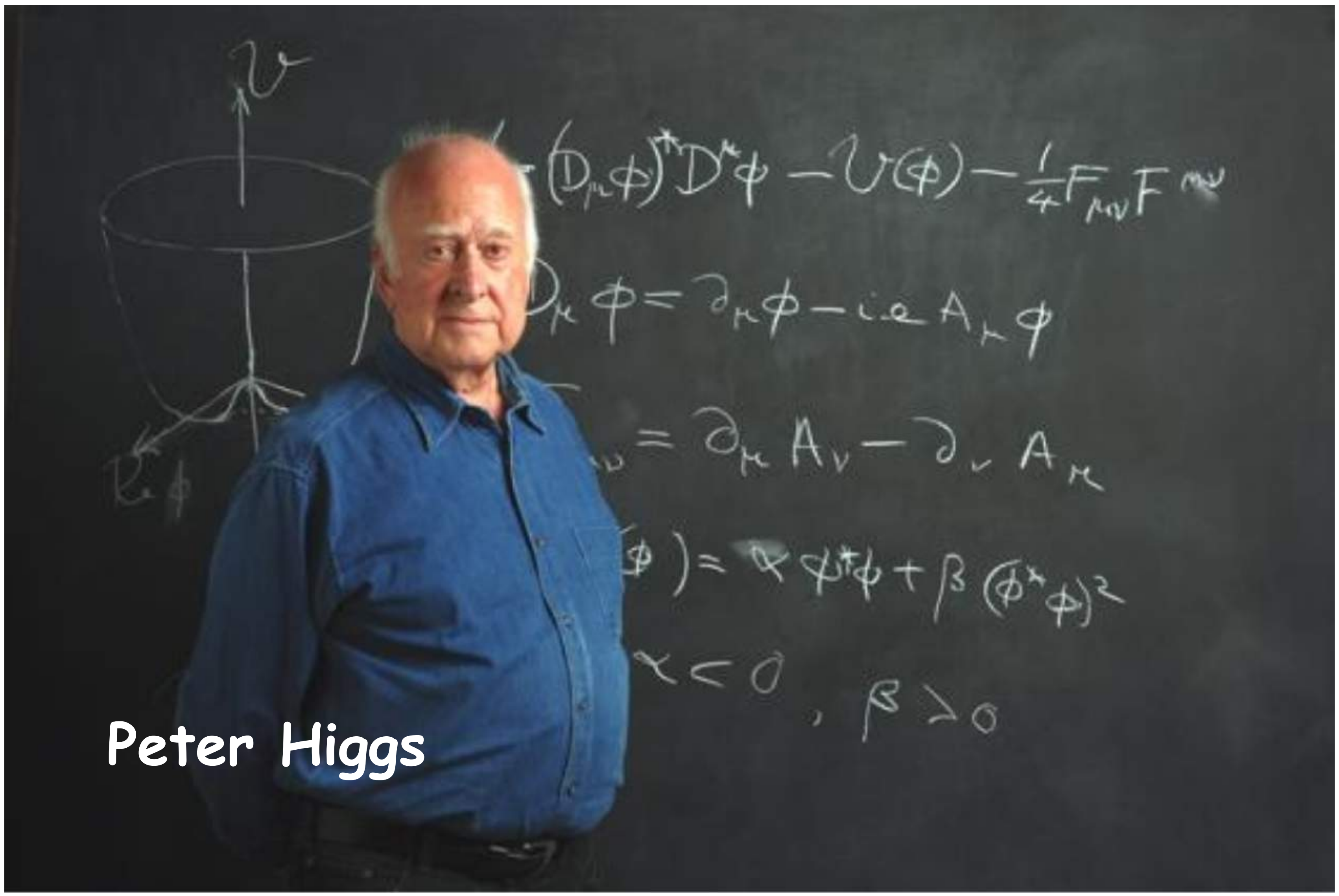
1) We have to understand how the mass for the elementary particles can be included in the model: **mass problem**

2) We have to understand why the 3 generations of quarks and leptons have so different masses: **flavor puzzle**

…with a big problem: where's the mass?

The mass problem is solved by introducing a new field: **the Higgs field**

P. Higgs, F. Englert, R. Brout '64



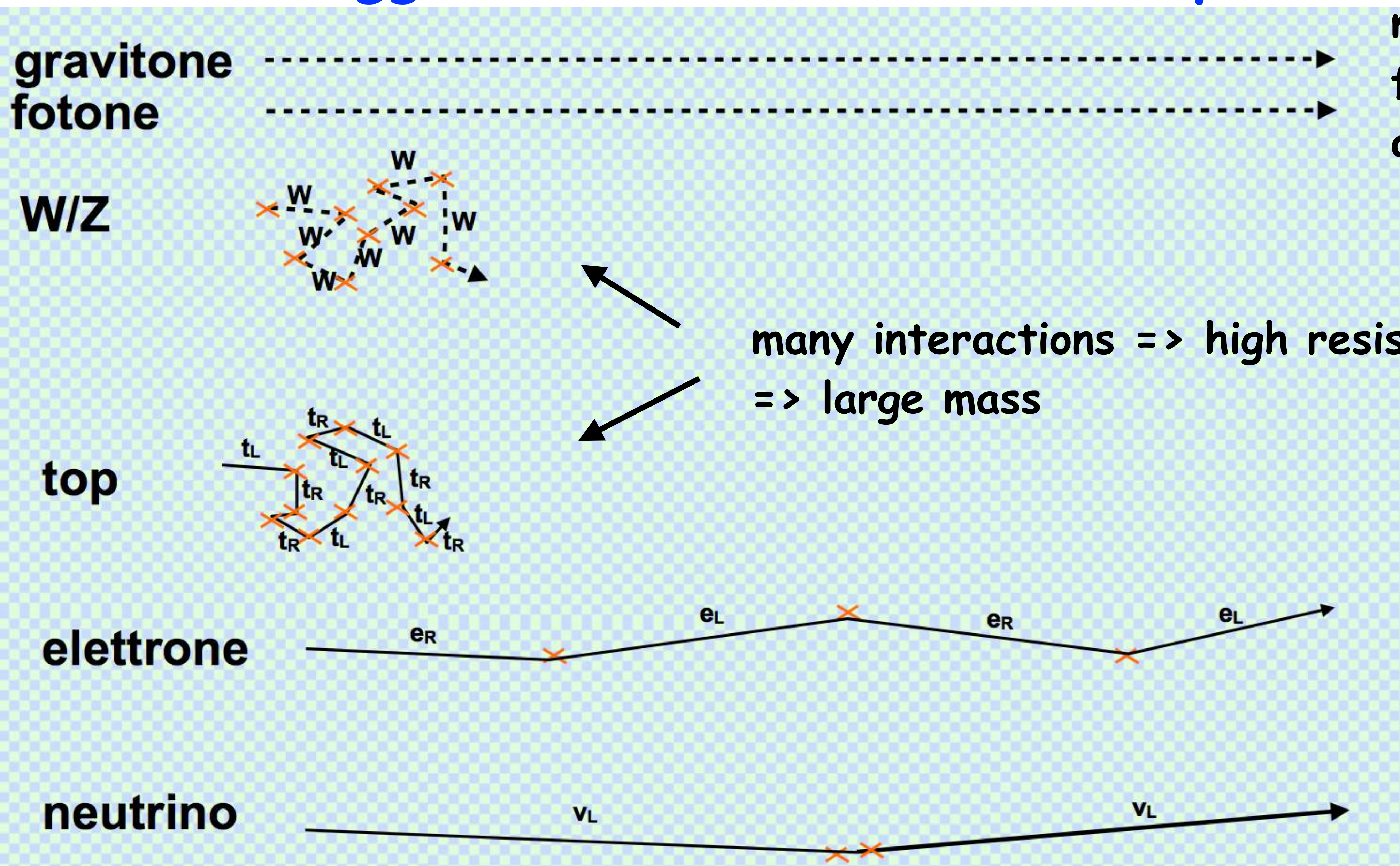
The elementary masses are then described as the result of the interaction of the various elementary particles with the Higgs field

(~ propagation in a viscous medium)

The Higgs mechanism

P. Higgs, F. Englert, R. Brout '64

The Higgs field fills the vacuum space



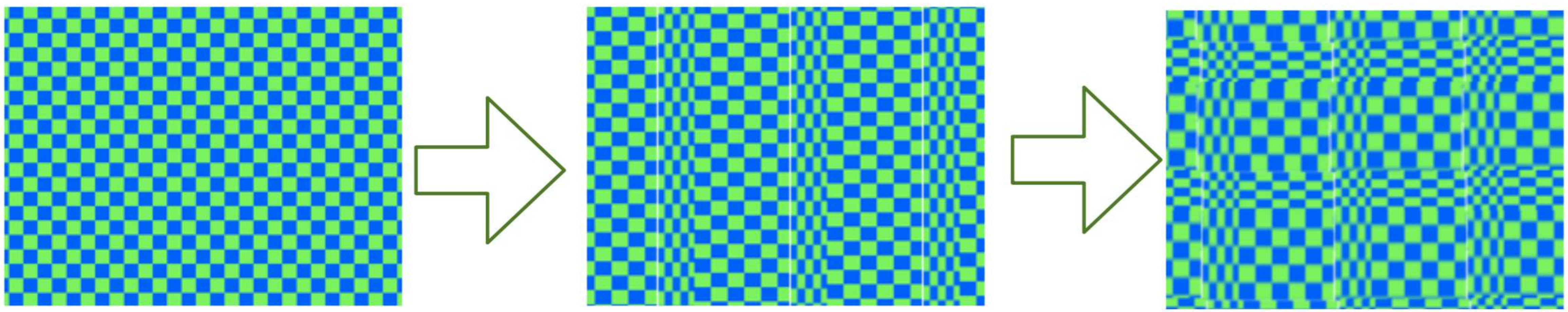
massless particles
fly undisturbed
at light speed

few interactions
=> low resistance
=> small mass

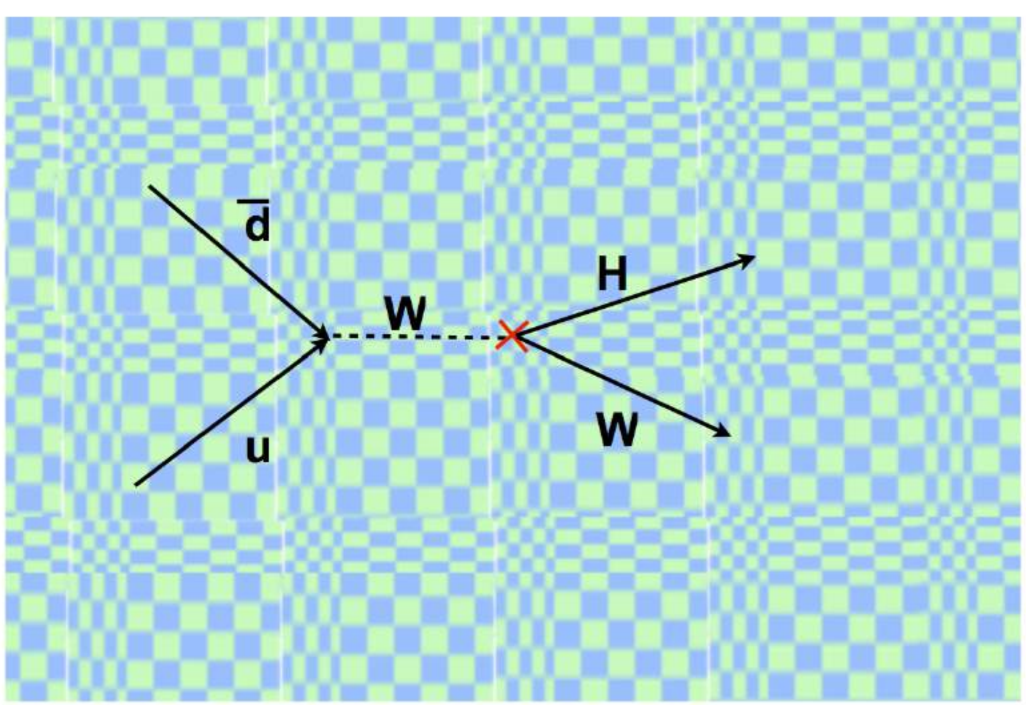
The reason for the different behaviour (= different masses) among the particles is not explained: **the Higgs mechanism does not solve the flavour puzzle**

The Higgs mechanism works, but…

We didn't know if the Higgs mechanism was a brilliant mathematical artefact, or described to some extent the reality, but…



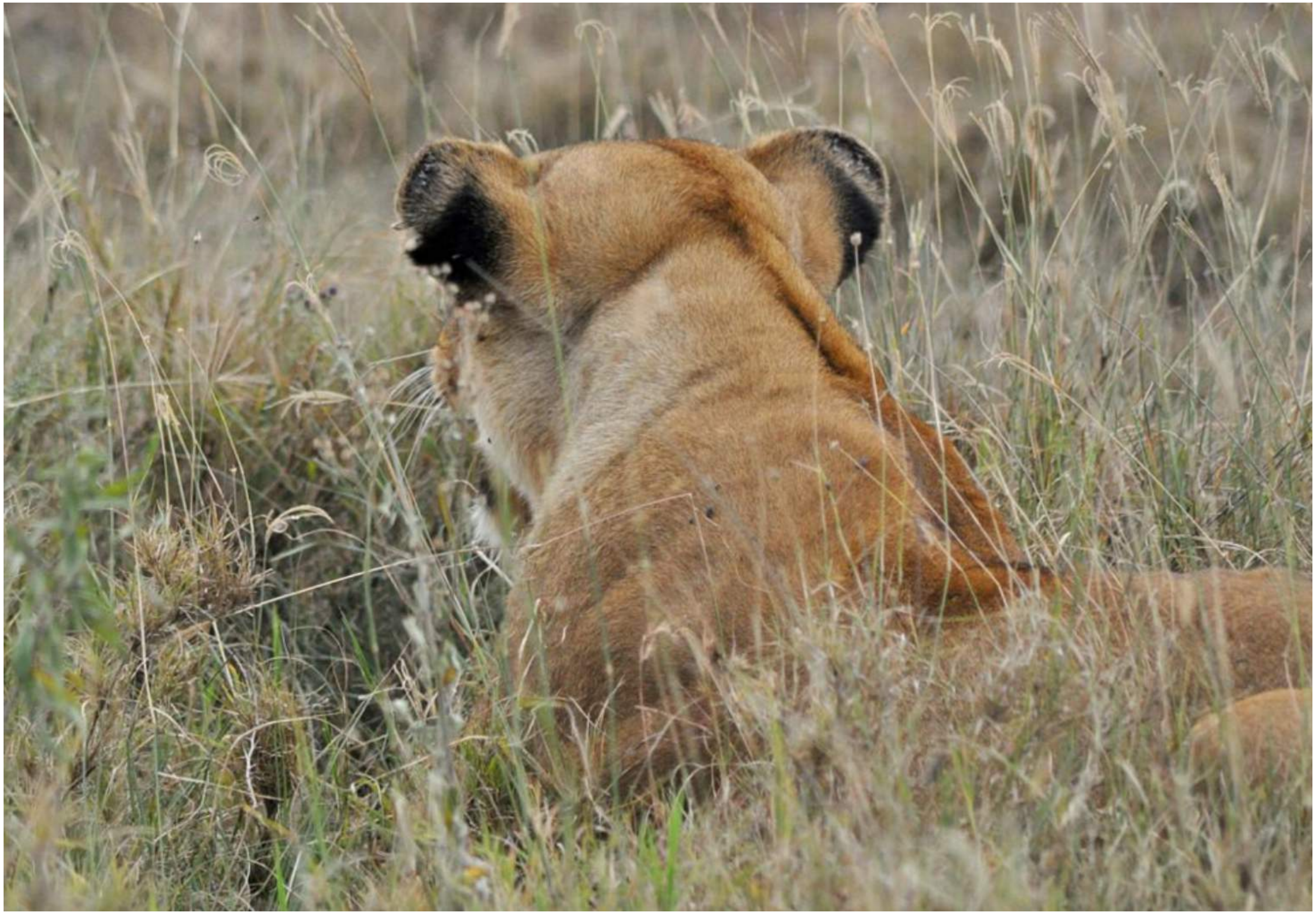
…fortunately, vacuum filled with Higgs field is not static: oscillations arise which, following **quantum mechanics**, represent a **new particle: the Higgs boson**



if we inject enough real energy in a single spacetime point we can produce and detect a Higgs boson… actually we should see it!!

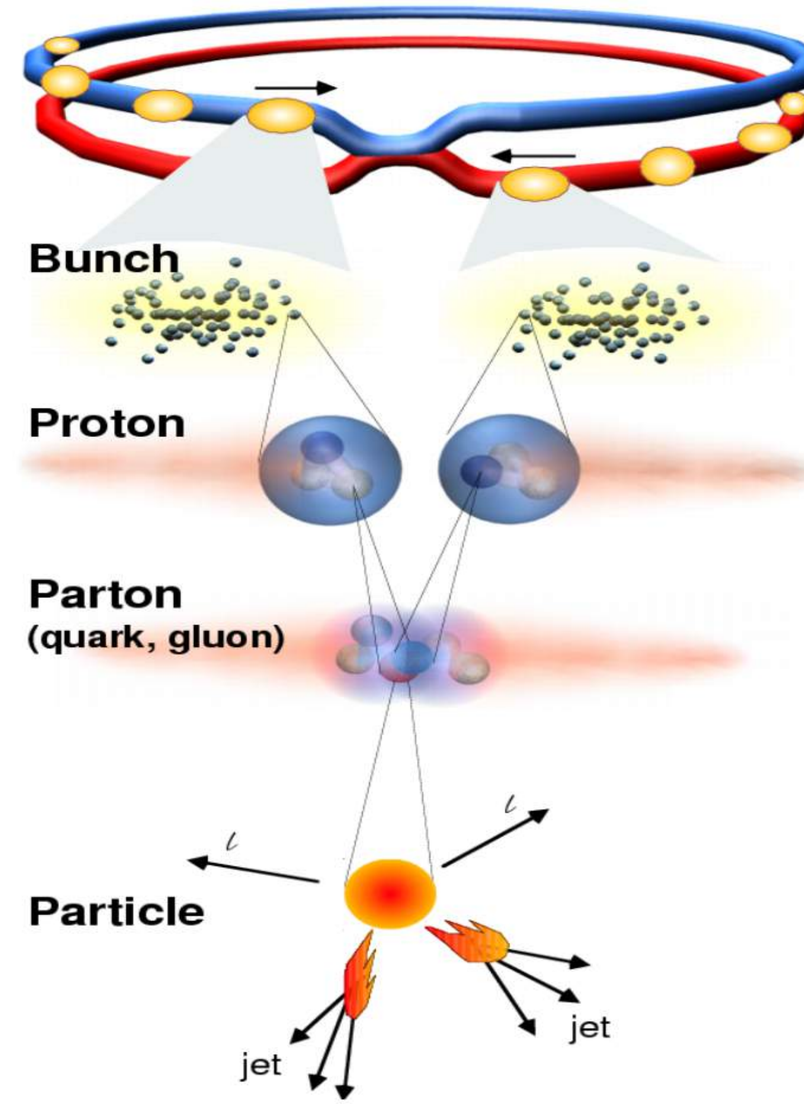
FOR THIS REASON THE LHC HAS BEEN BUILT

The hunt to the Higgs boson is open!



The hunt to the Higgs boson is open!

1) we need a powerful accelerator to make protons collide at the highest possible energy and intensity

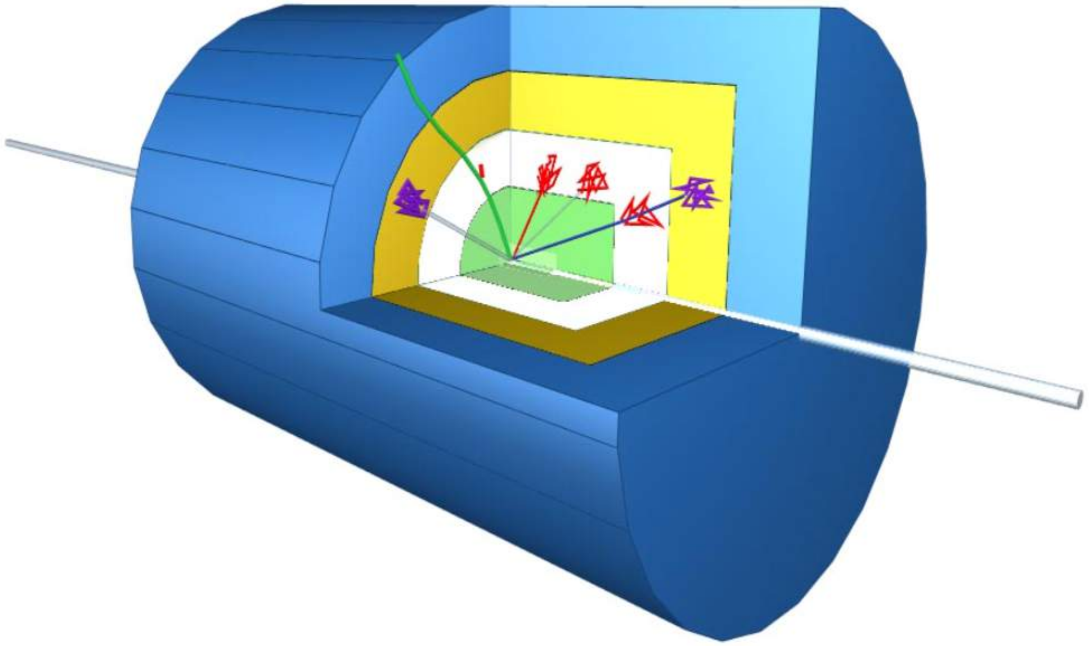


LHC in numbers:

3x10^{14} protons per beam
7 TeV is the proton energy
350 MJ is the total energy stored in the beam: a train which travels at 150 km/h!!

The hunt to the Higgs boson is open!

2) we need gigantic detectors capable to capture and register all of the particles produced in the collision, measuring their energies and trajectories

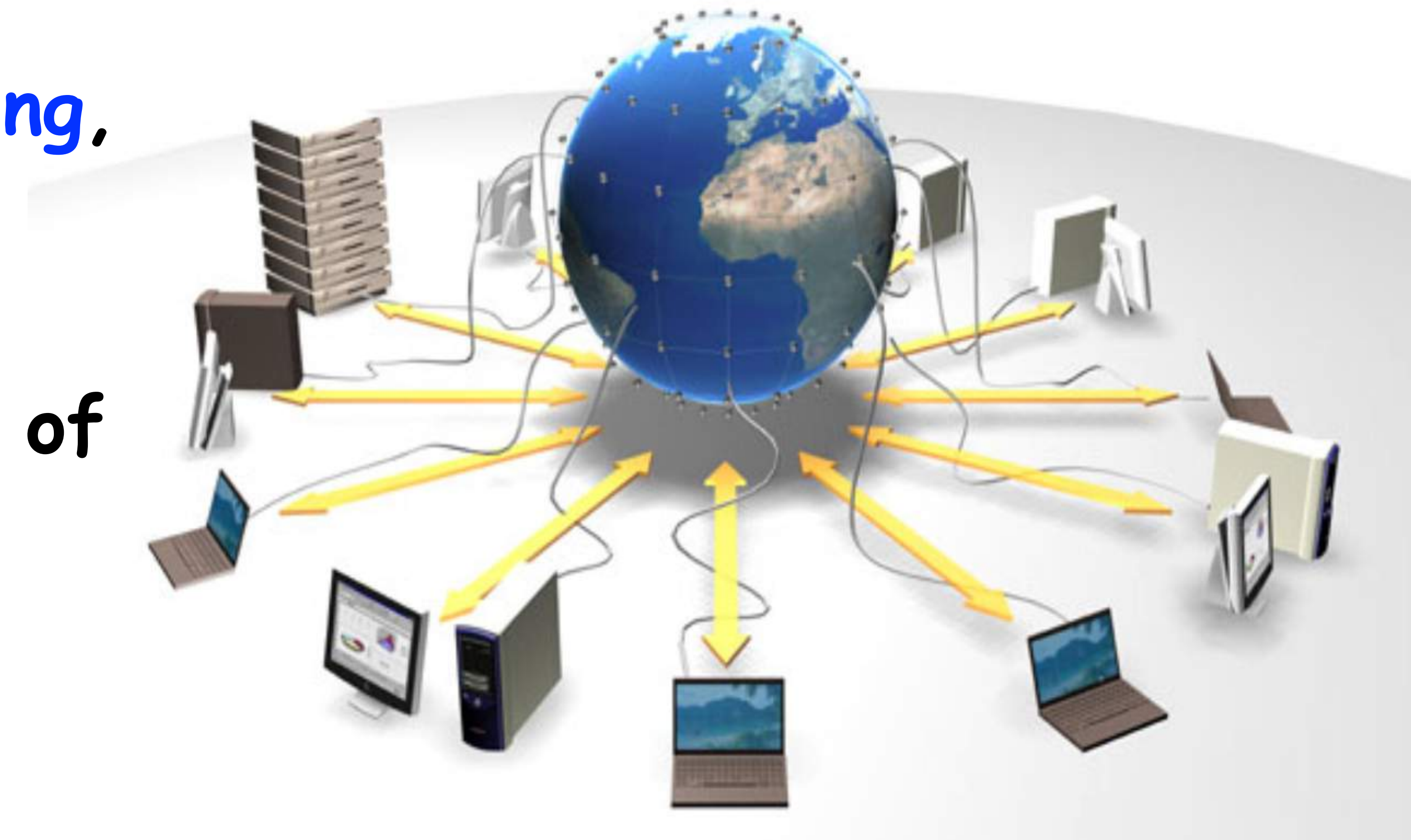


LHC detectors in numbers:

The detectors installed at LHC are like digital camera's as large as a **five floors building**, with **100 Megapixels**, and capable to make **40M pictures per sec**!

The hunt to the Higgs boson is open!

3) we need **supercomputing**, to collect, store and distribute (all over the world) the huge amount of data produced by the detectors



LHC computing in numbers

- The detectors are like digital camera's with 100 Megapixels which make 40M pictures/sec
- After a first selection: 100,000 pictures/sec ~1 Mbyte each
- Analysed on a farm of Intel processors with **50,000 CPU** cores
- Each second, the 200-300 best pictures are recorded on disk: **10,000 Tbytes per year!!!**

The hunt to the Higgs boson is open!

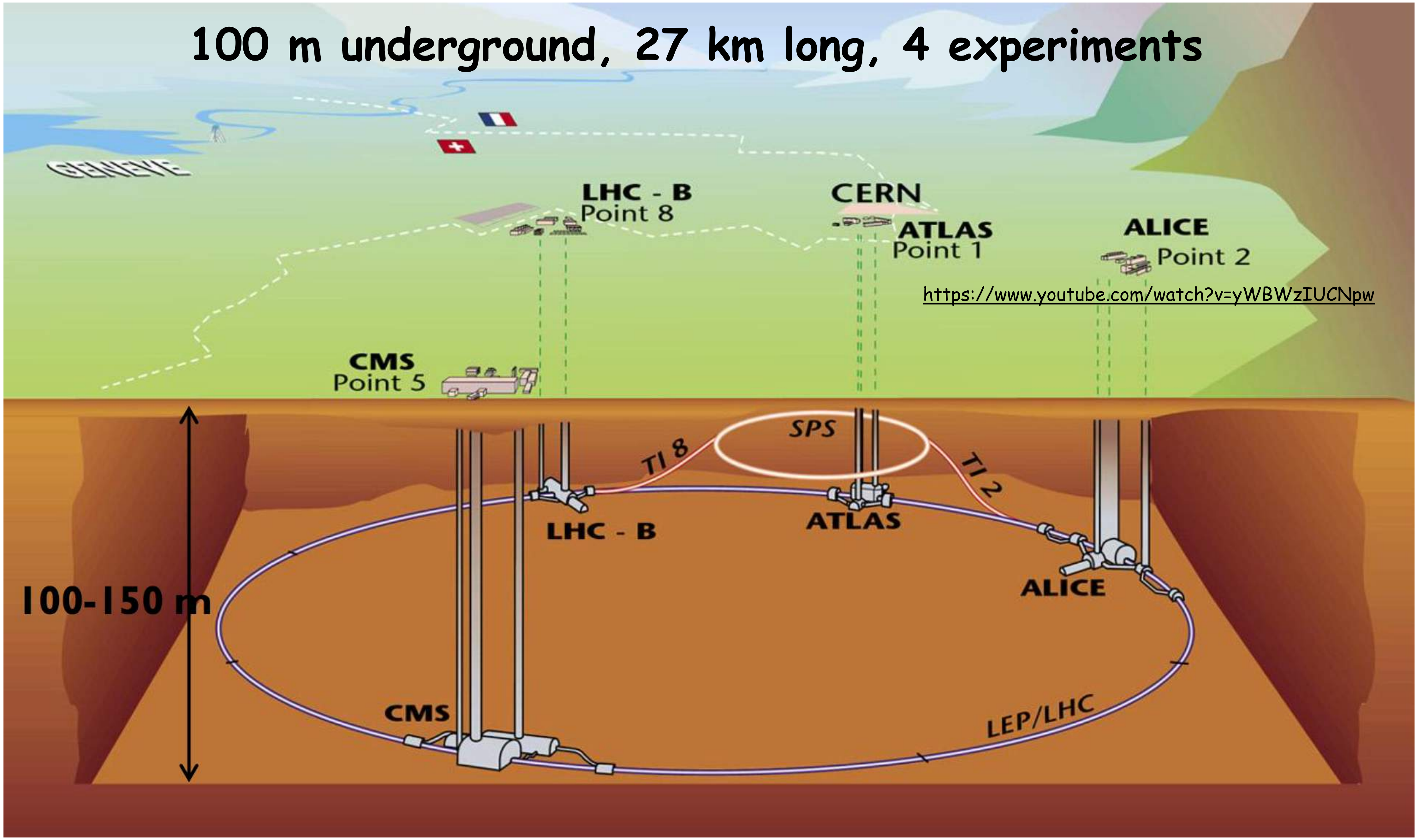
4) we need large collaborations, involving thousands of people, physicists, engineers and technicians, to design, build and operate such huge and complex machines

ATLAS/CMS building at CERN

The 4 LHC collaborations in numbers

- ATLAS: 3000 scientists, 37 countries, 167 institutions
- CMS: 3000 scientists, 180 institutions
- ALICE: 1000 scientists, 30 countries, 105 institutions
- LHCb: 600 scientists, 40 institutions

Under the LHC tunnel



- **CMS and ATLAS**: Higgs search, direct observations of new massive particles
- **LHCb**: understanding why the antimatter has disappeared
- **ALICE**: quark-gluon plasma (early stage of the universe, just after Big Bang)

The accelerator

Credits: Asimmetrie

The main components of an LHC-type particle accelerator:

a) radio-frequency accelerating cavities

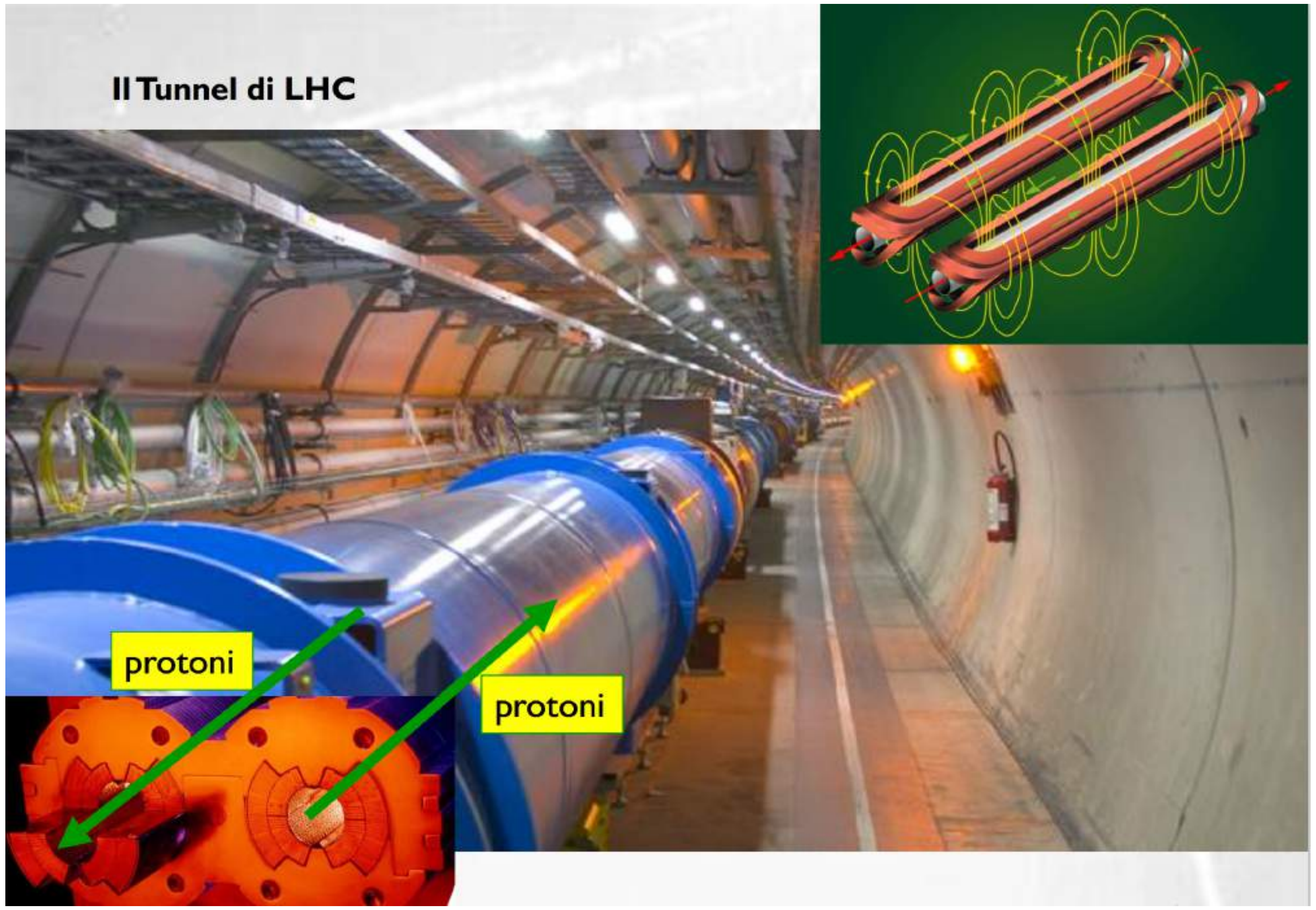
b) **dipole magnets** to guide the proton beam in a circular orbit

c) quadrupole magnet to focus the beam

d) detectors

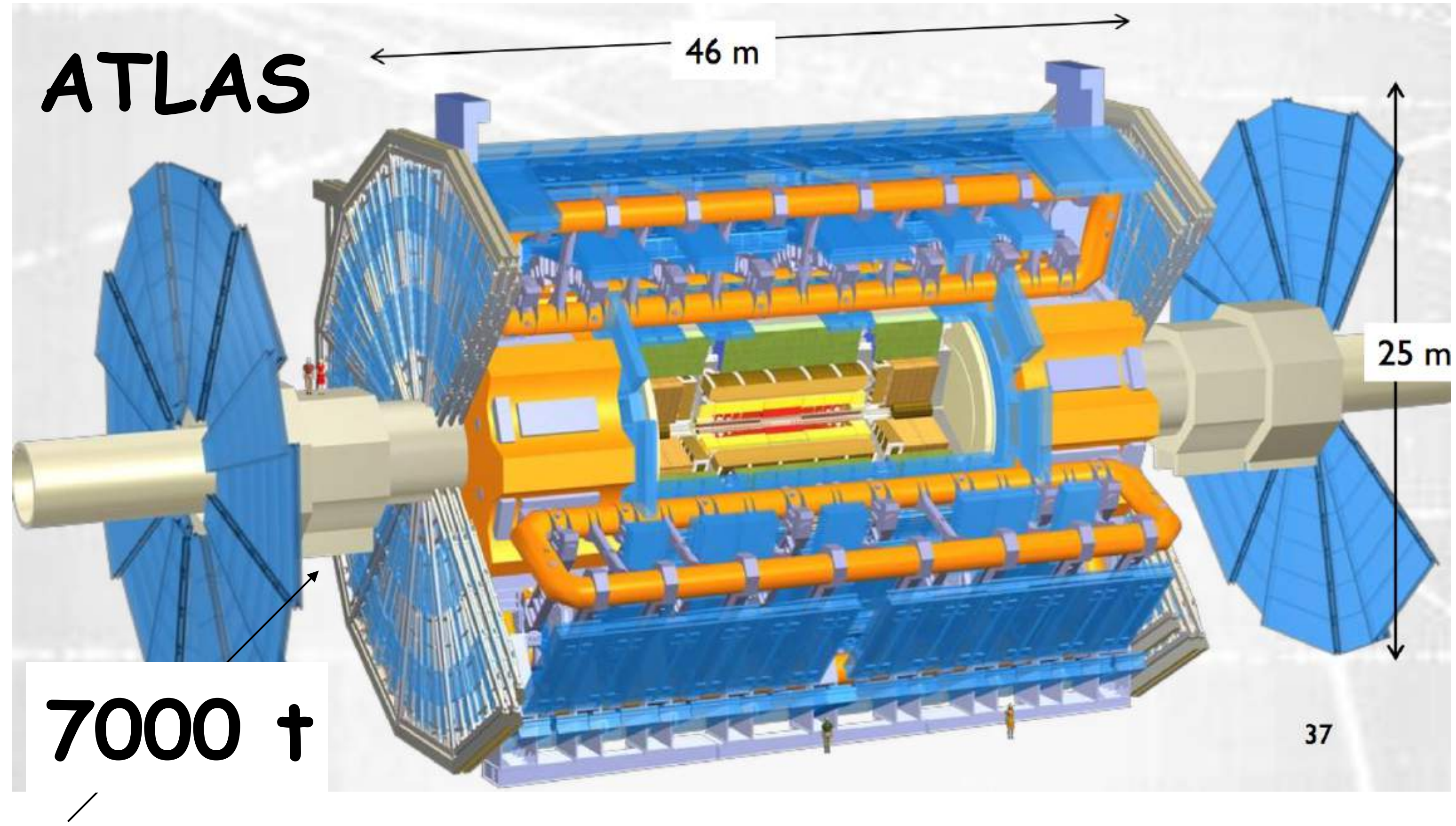
The heart of the LHC is made of **1200 dipole magnets** installed along the ring to bend the protons:

- magnetic field is **8.3 Tesla**
- magnets are superconducting, and work at a temperature of **1.9 Kelvin** (-271 Celsius), with superfluid helium



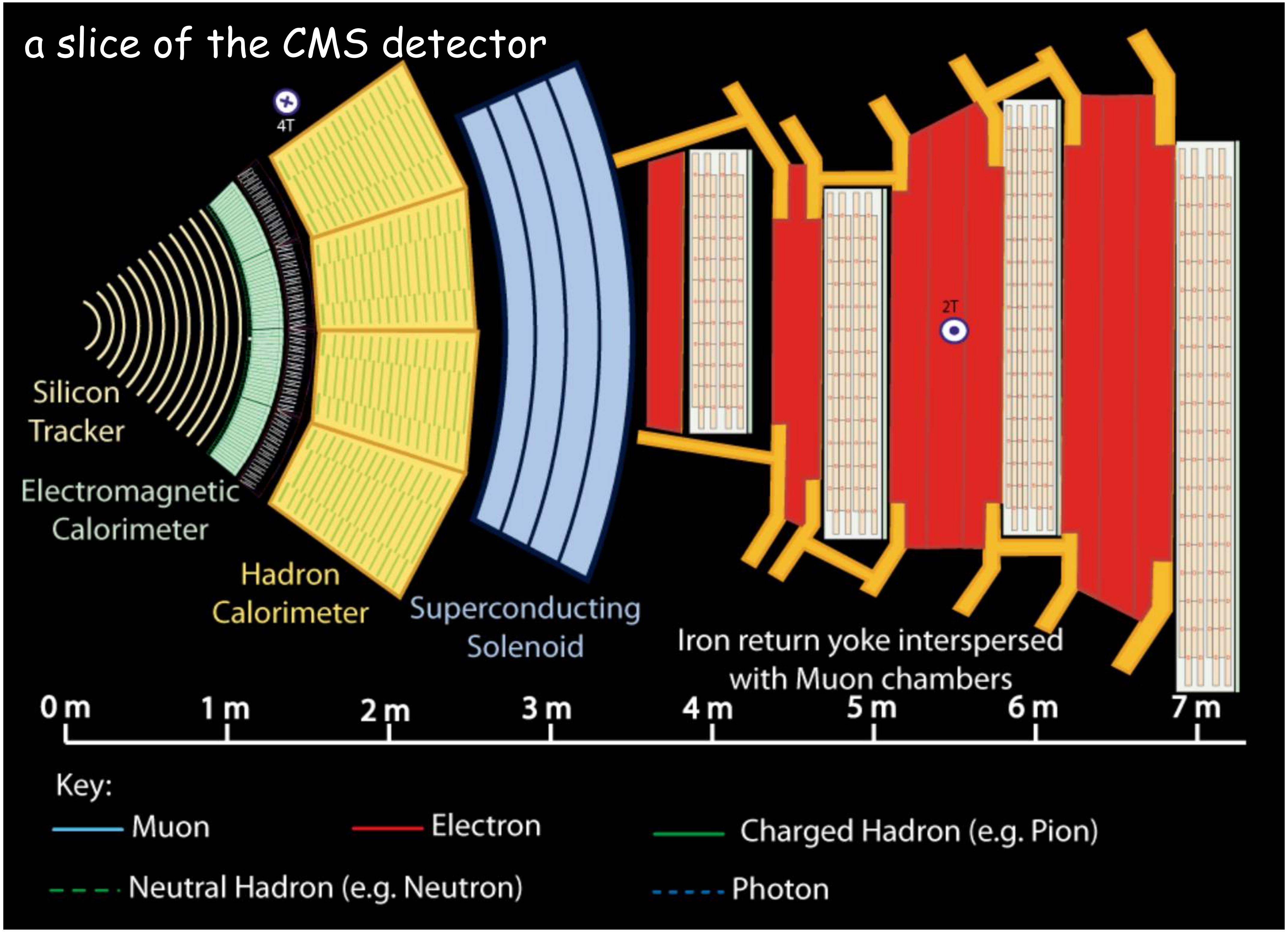
THE COLDEST PLACE IN THE UNIVERSE

The detectors

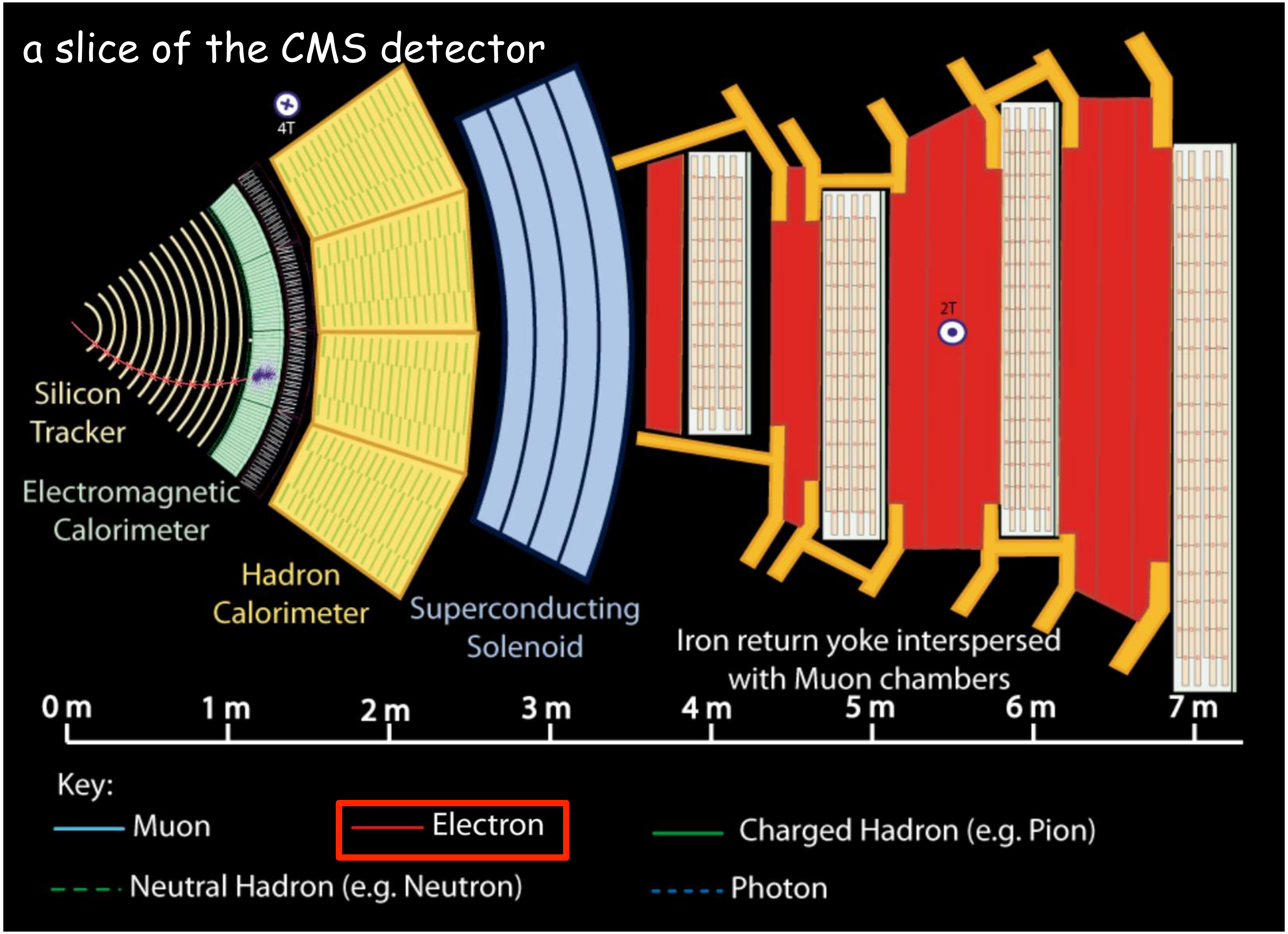


- The detectors are made of concentric layers of sensors around the collision point
- Each layer is able to detect/identify a different type of particle created in the collision, measuring its energy/position

Measuring the invisible

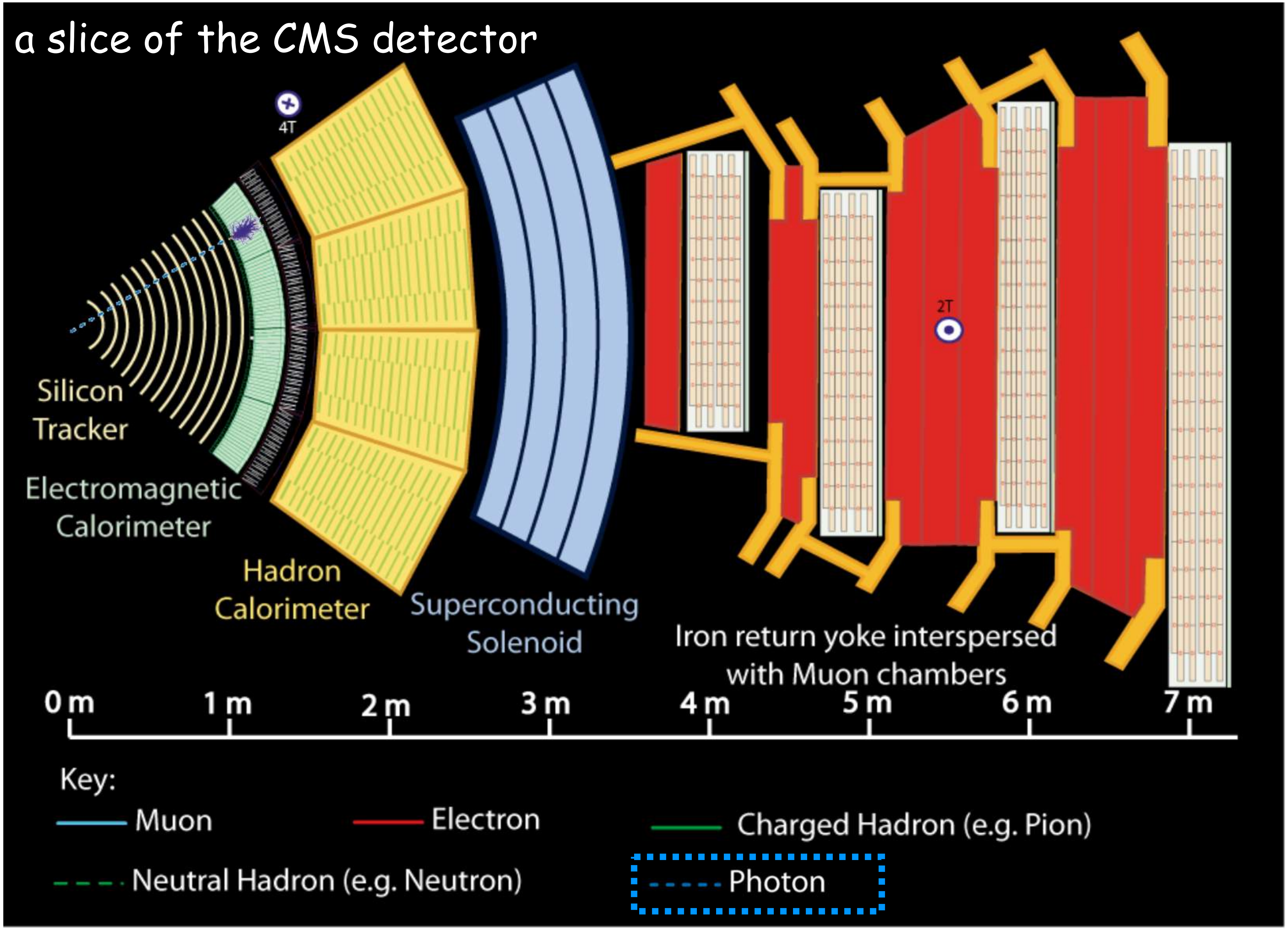


Measuring the invisible



the magnetic field bends the charged particles, allowing the momentum measurement

Measuring the invisible



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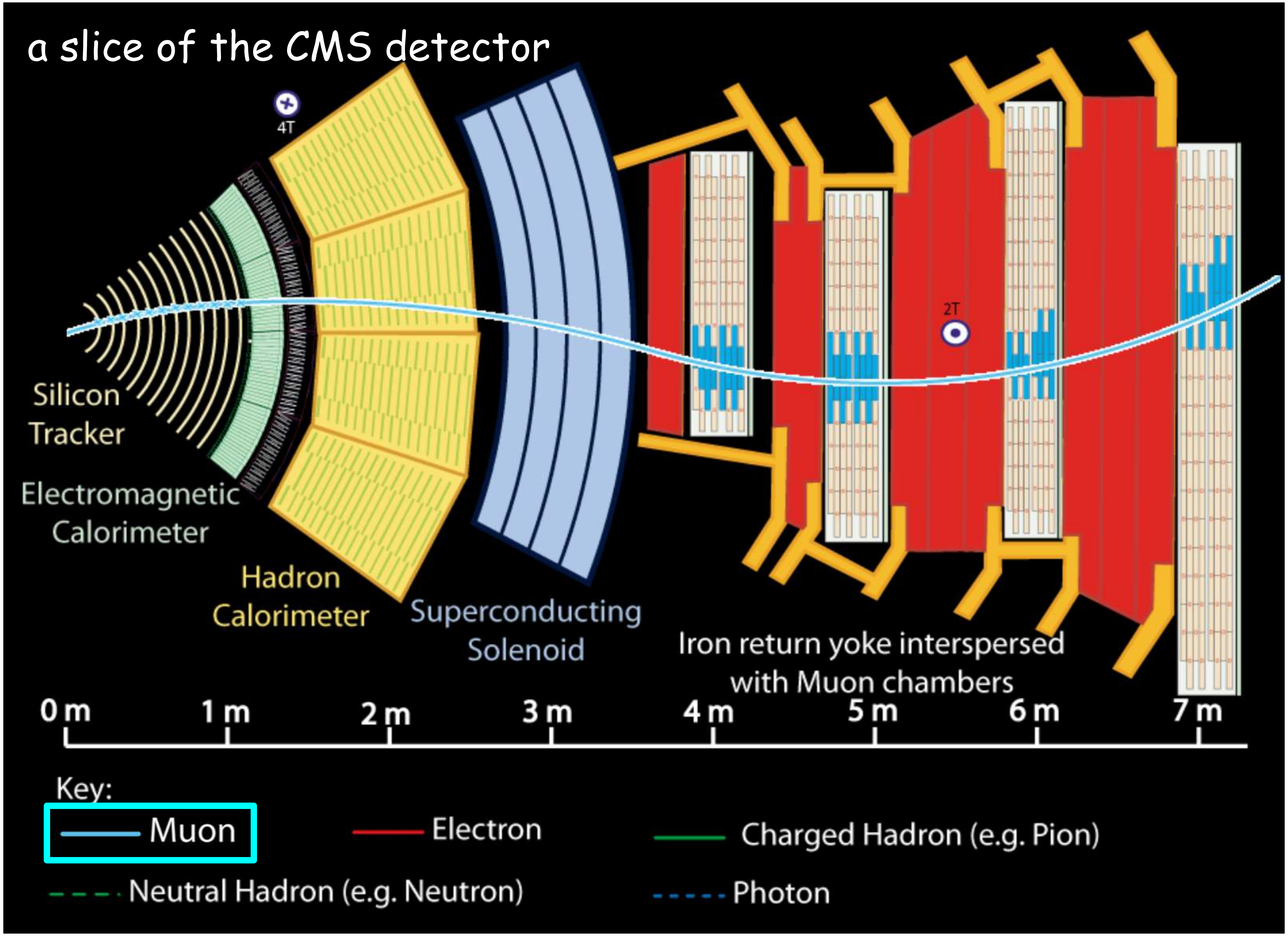
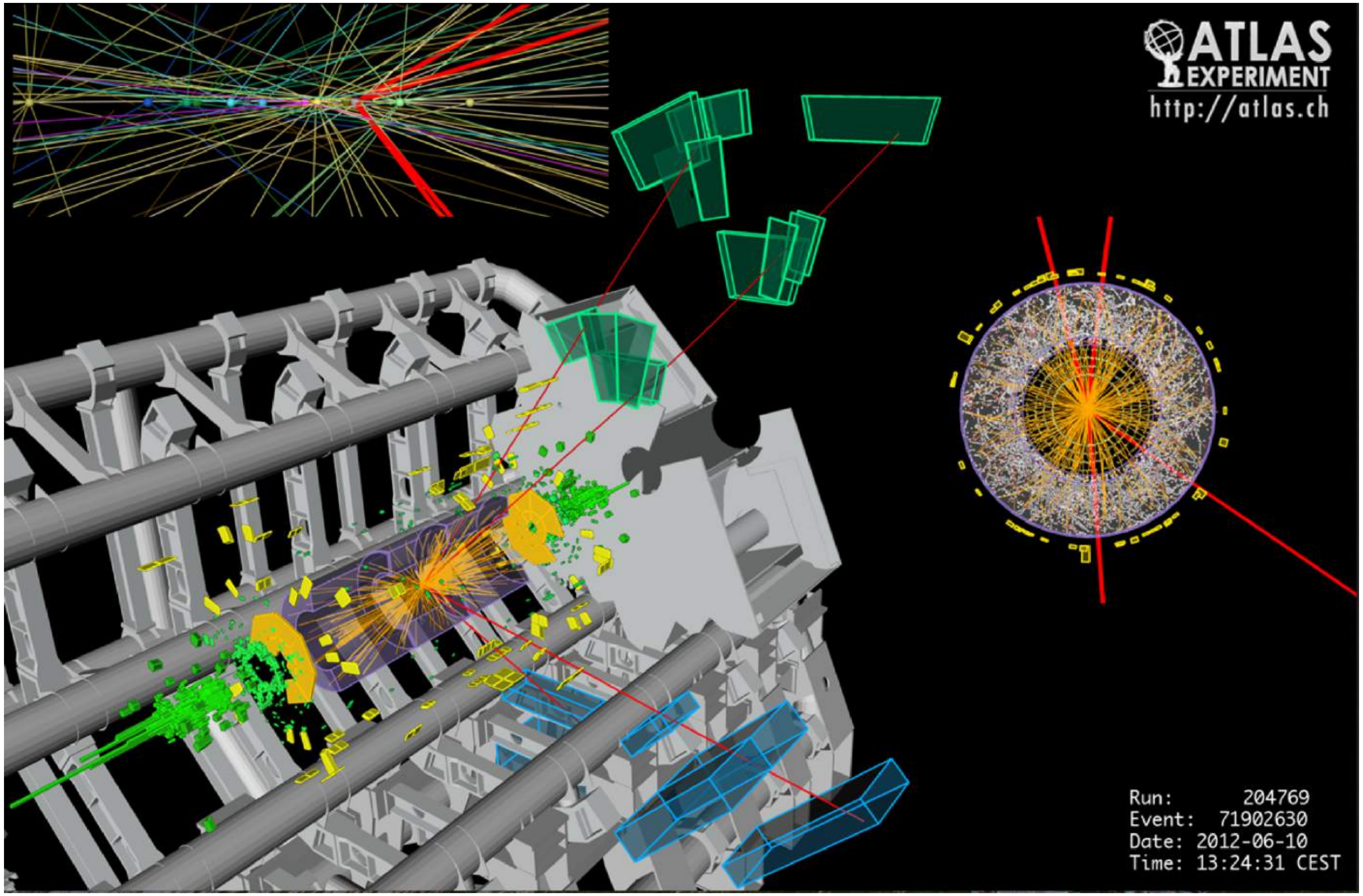


...and this is the result!



each picture ("event") is identified by two numbers: #RUN and #EVENT

4 high energy muons produced in a proton-proton collision as seen by the ATLAS experiment: **do they come from a disintegration of an Higgs boson created by LHC? how can we understand this?**

The trick: accumulate many "4 muon events"

Actually, the category of events in which we're interested is more general:

$\mu^+\mu^-\mu^+\mu^-$ 4 muons

$e^+e^-e^+e^-$ 4 electrons

$\mu^+\mu^-e^+e^-$ 2 muons + 2 electrons

4 leptons!

Having measured the energy and the momentum of the 4 leptons, and making the hypothesis they come from the disintegration of a single particle, we're able to calculate its mass, following Einstein law of energy-mass conservation…**let's have a look to the result!**

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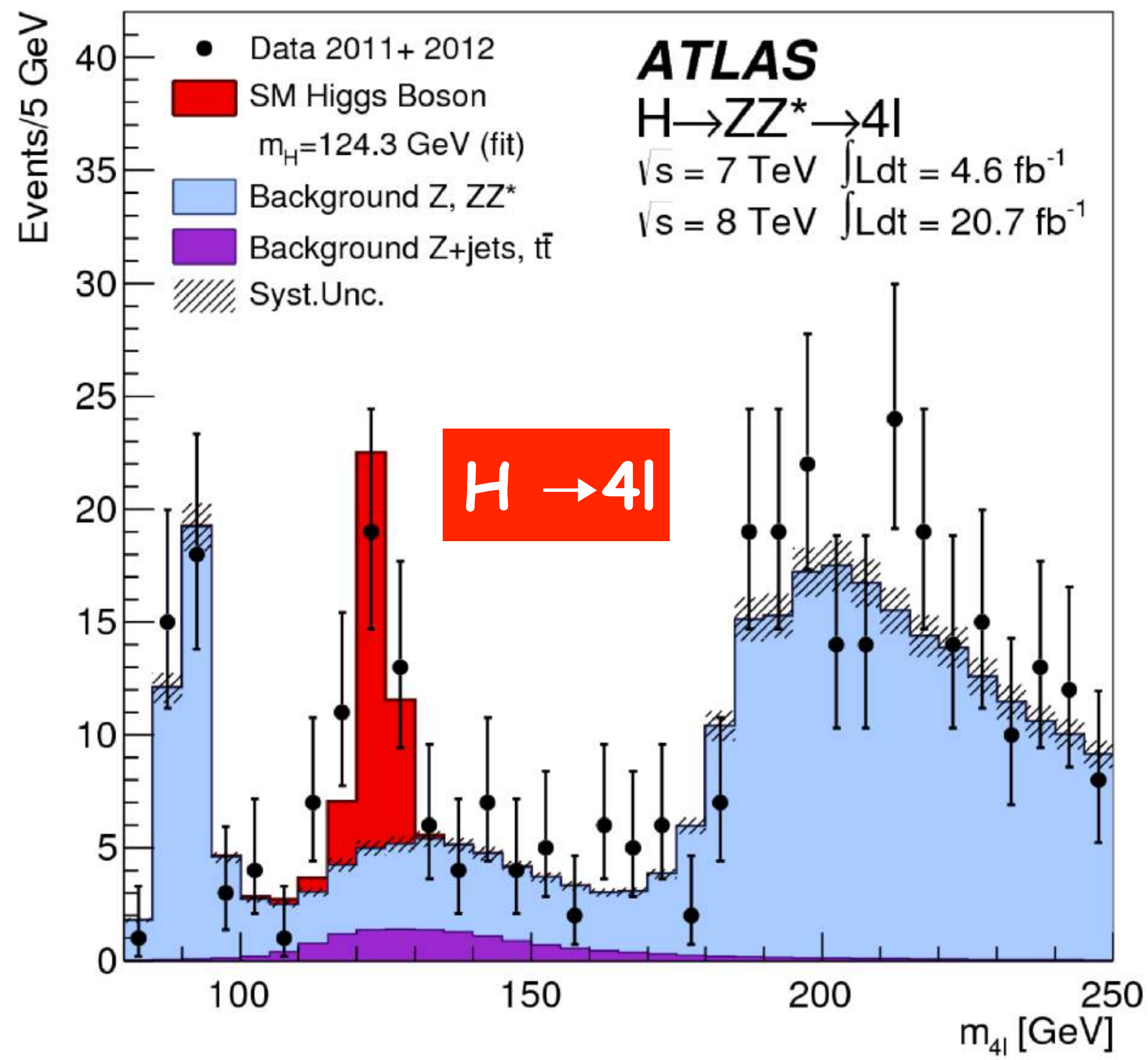

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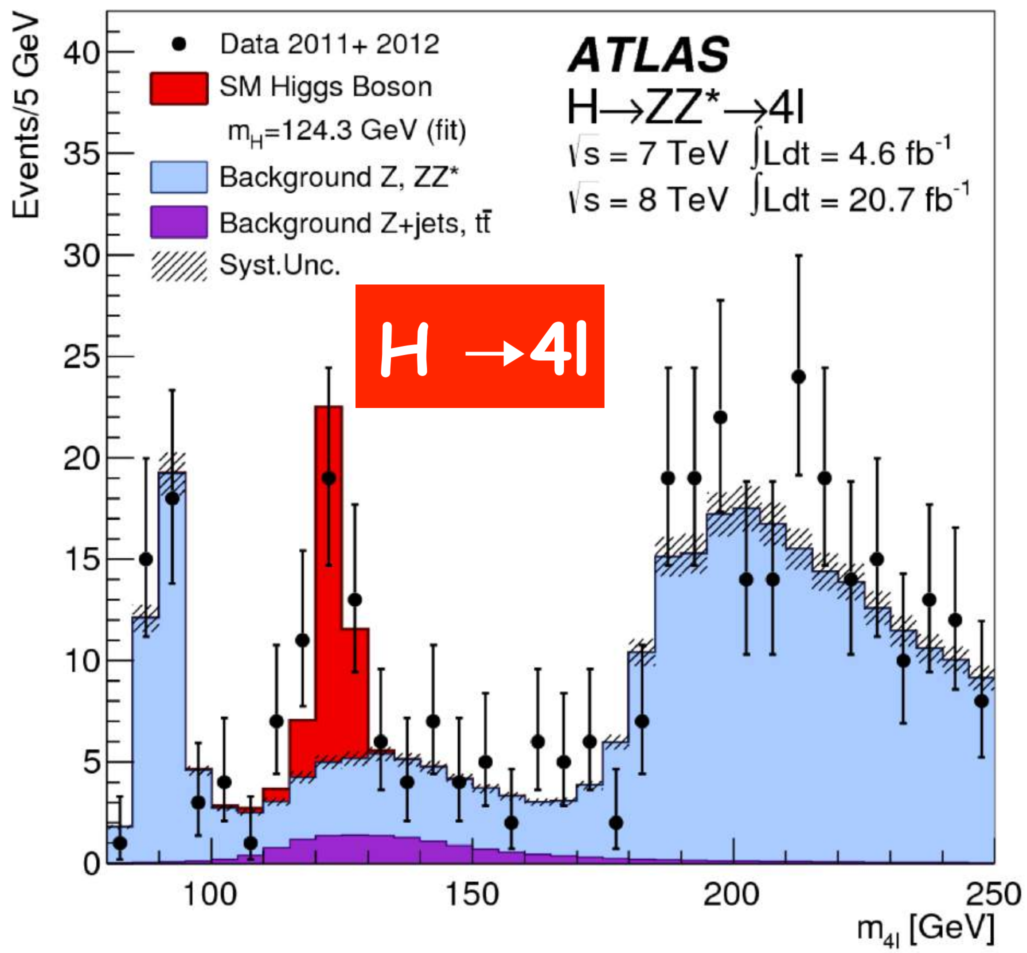
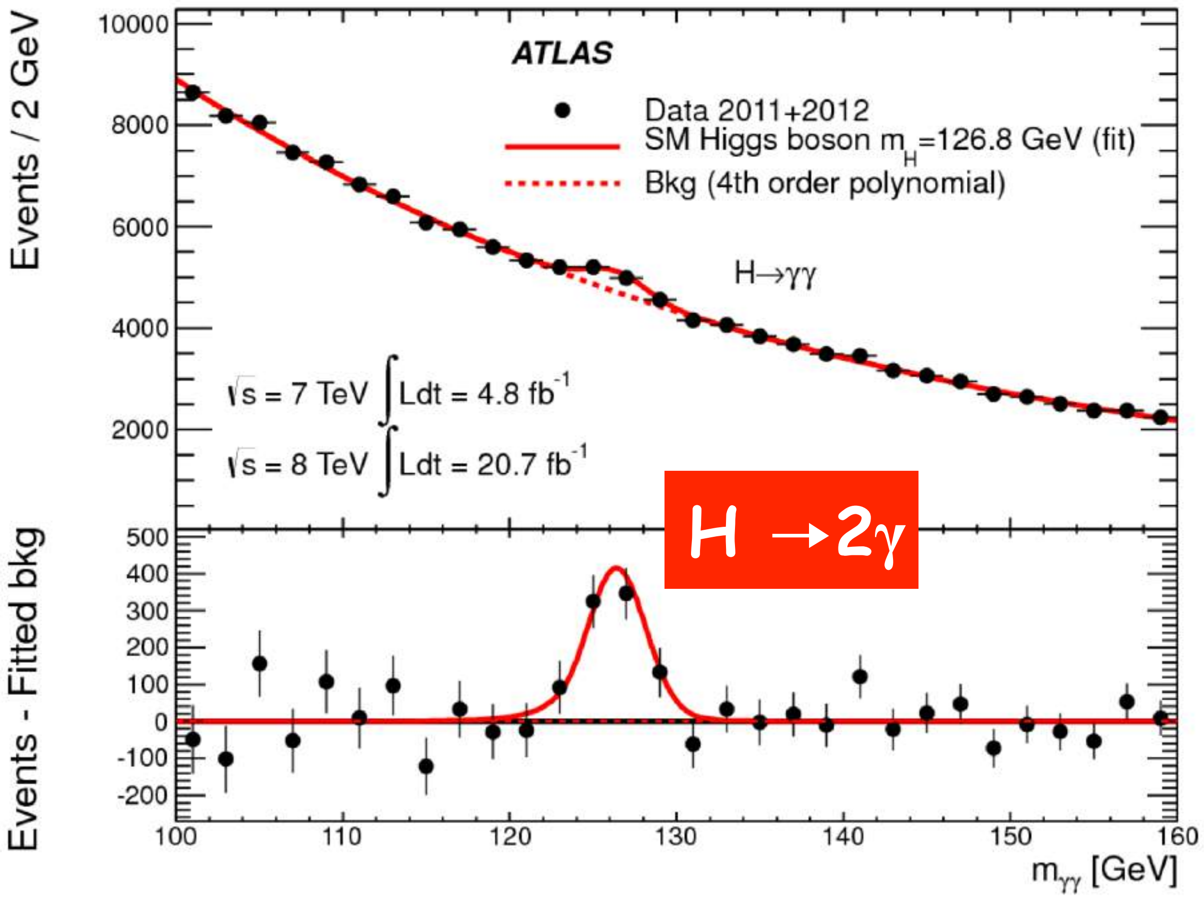
Higgs discovery…

The search is repeated using **different hypotheses** for the Higgs disintegration



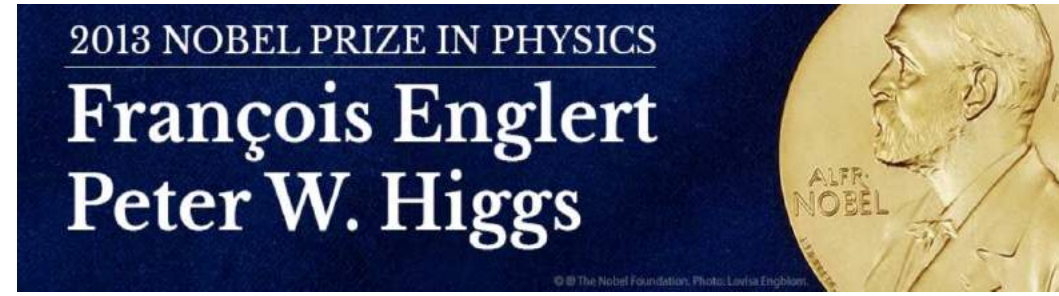


Indeed a peak with the same mass~**126GeV** is found also in two photon events!!

The same results have been observed by **ATLAS** and **CMS** experiments:

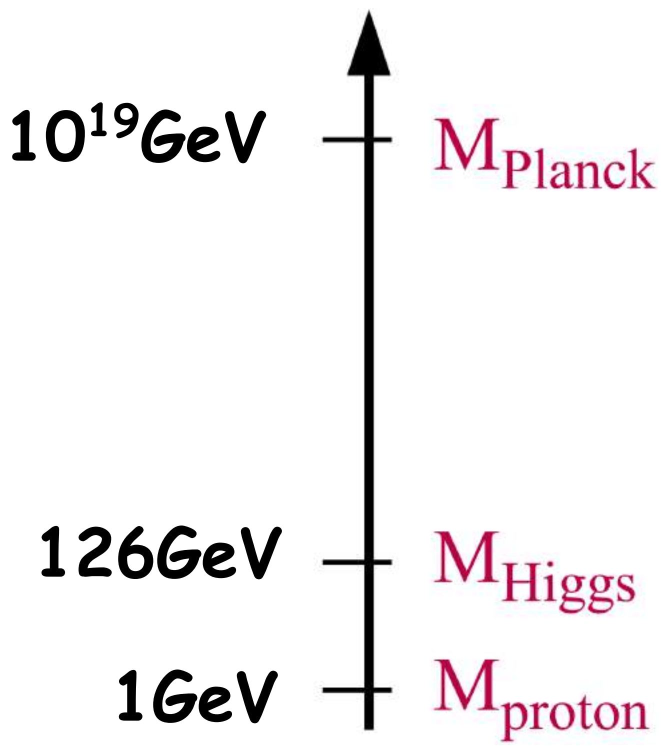
THIS IS THE TRIUMPH OF THE STANDARD MODEL

...and now you can get your Nobel prize!!



Higgs discovery is announced at CERN, 4th of July 2012

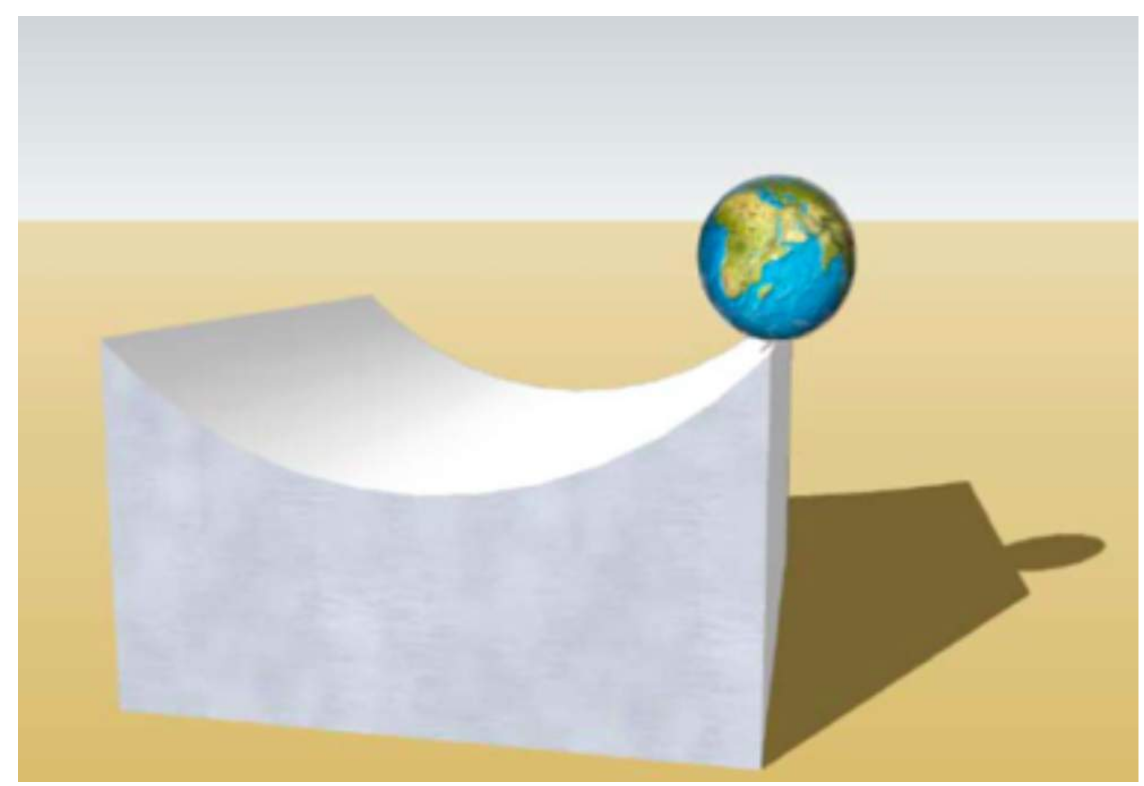
Is this the end of the story?



The Higgs boson mass (126 GeV) is large as compared to the proton mass (~1 GeV), but is still well below the Planck energy scale, $M_{Planck} \sim 10^{19}$ GeV, which is where we do expect the gravity becoming relevant to the interactions of elementary particles

Why $M_{Higgs} << M_{Planck}$?

Can we extend the validity of the Standard Model up to energies ~M_{Planck}? The answer is yes, but in absence of new phenomena (particles) **the Higgs mass value and the universe are unstable…**



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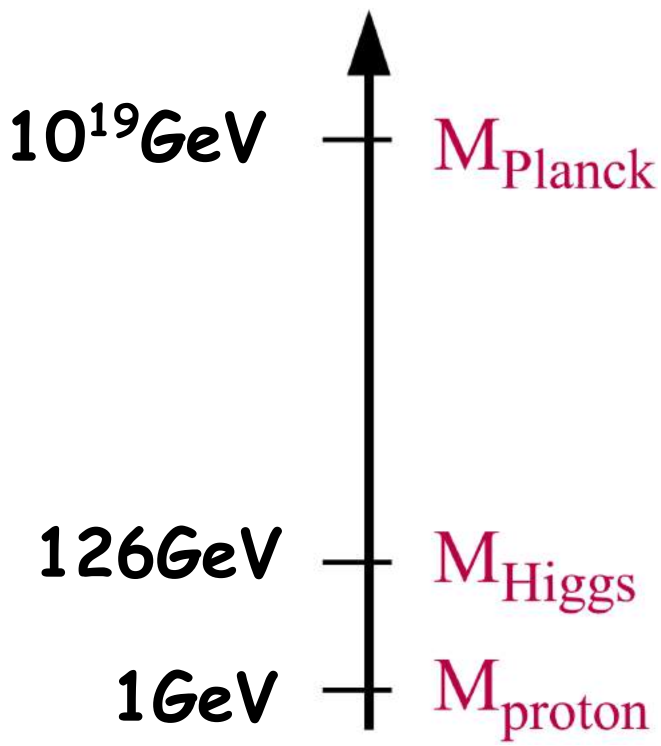

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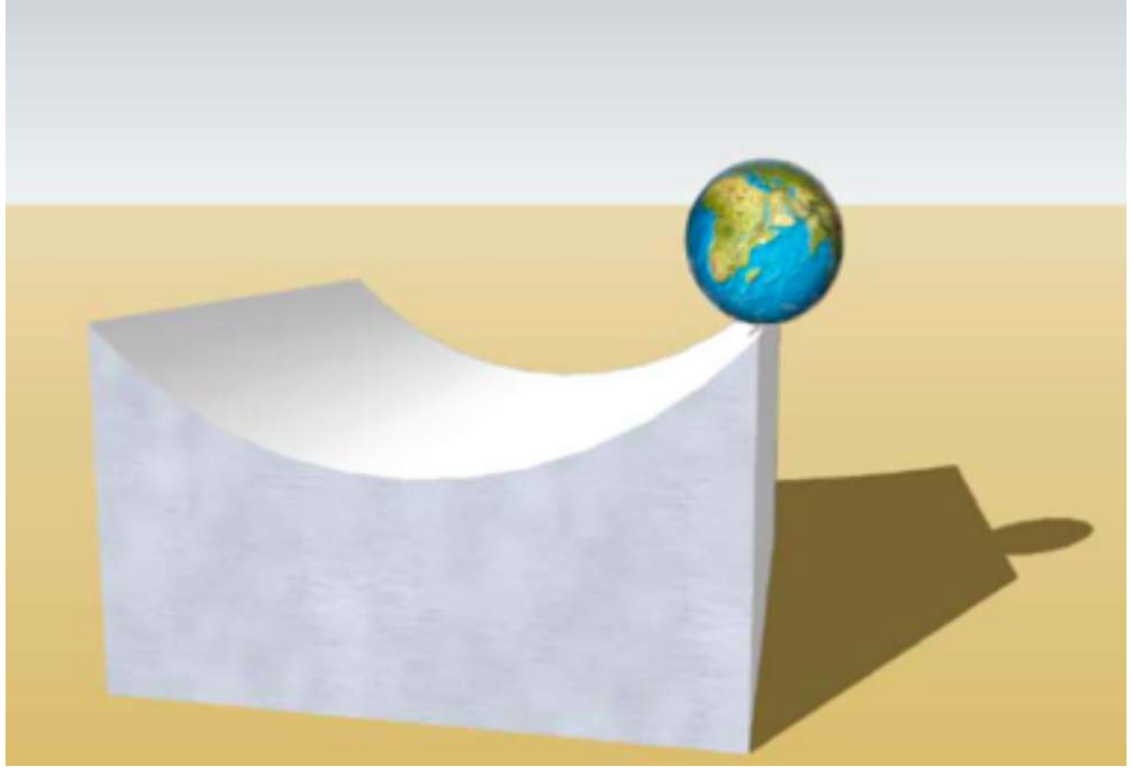
Why $M_{Higgs} << M_{Planck}$?

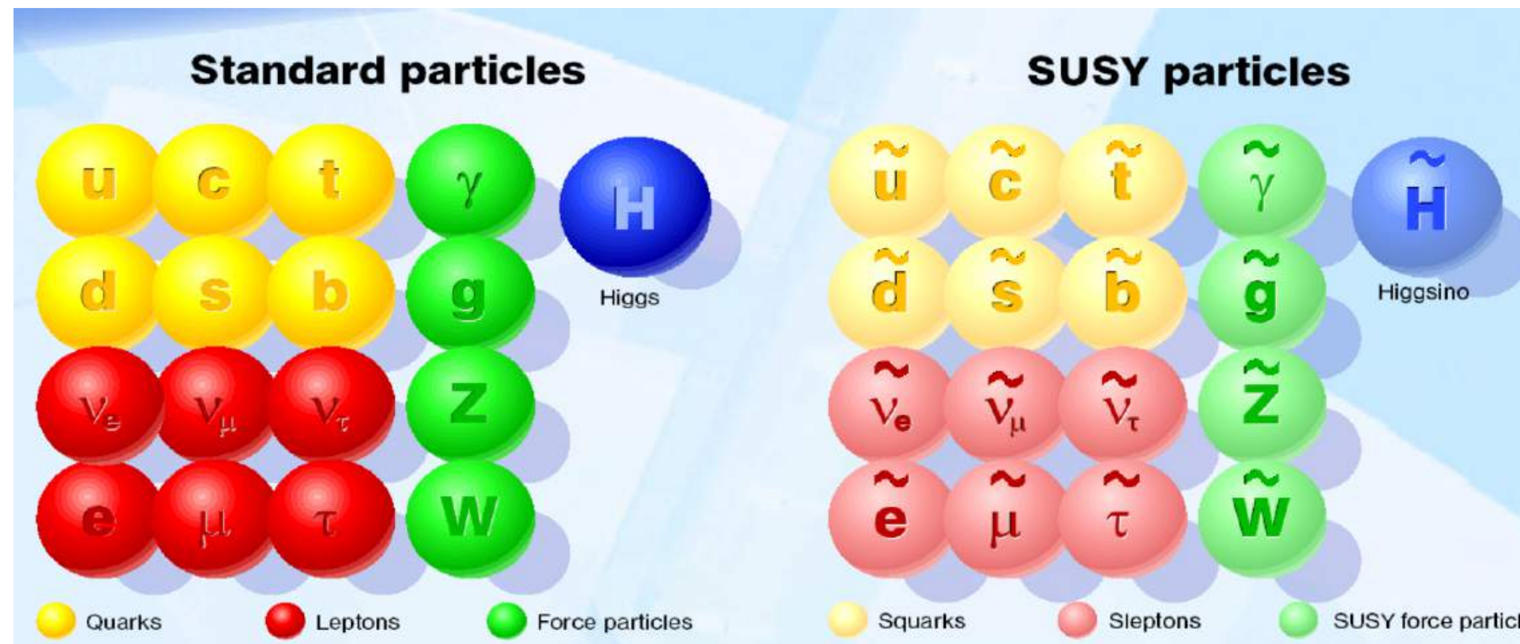
…**don't worry!**… the lifetime of this unstable configuration is expected to be much longer than the present age of the universe (13×10^9 years)



We want a "more natural" universe

The physicists (**especially theoreticians**) do not like the unstable solutions (**our** experience tell us that nature usually tends to prefer stable minima), so several extensions of the Standard Model have been proposed which avoid this problem

One of the most popular invokes the so called **SuperSymmetry (SUSY)**, which predicts that for each particle of the SM a **SUSY partner** exists with the same properties but different spin

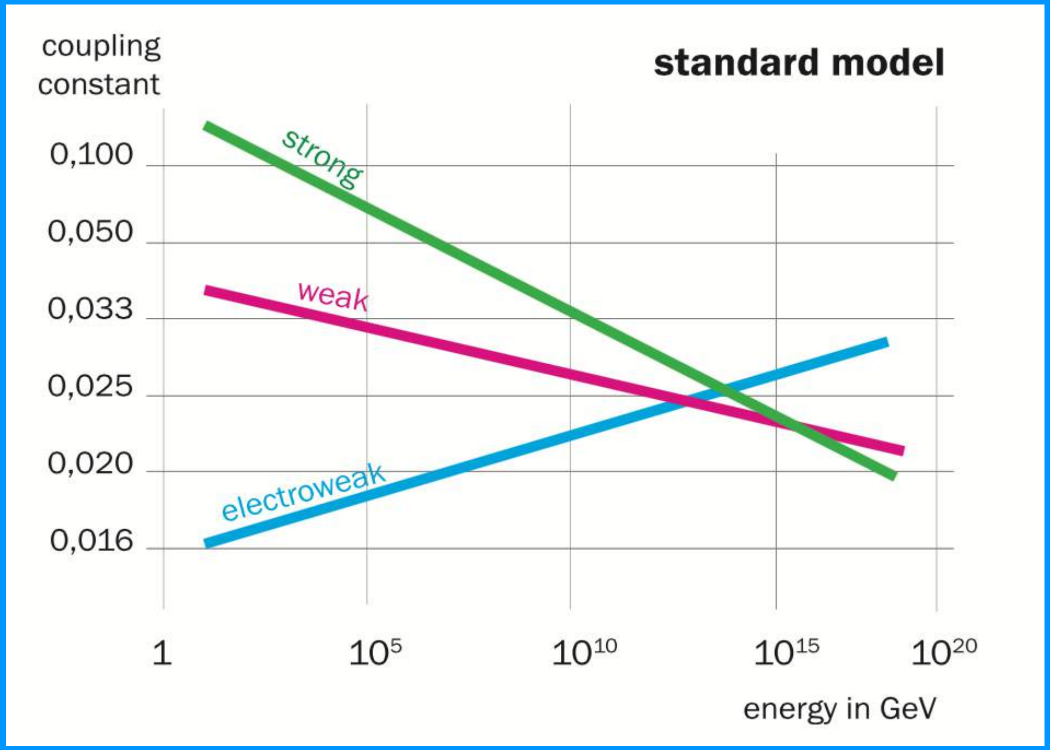


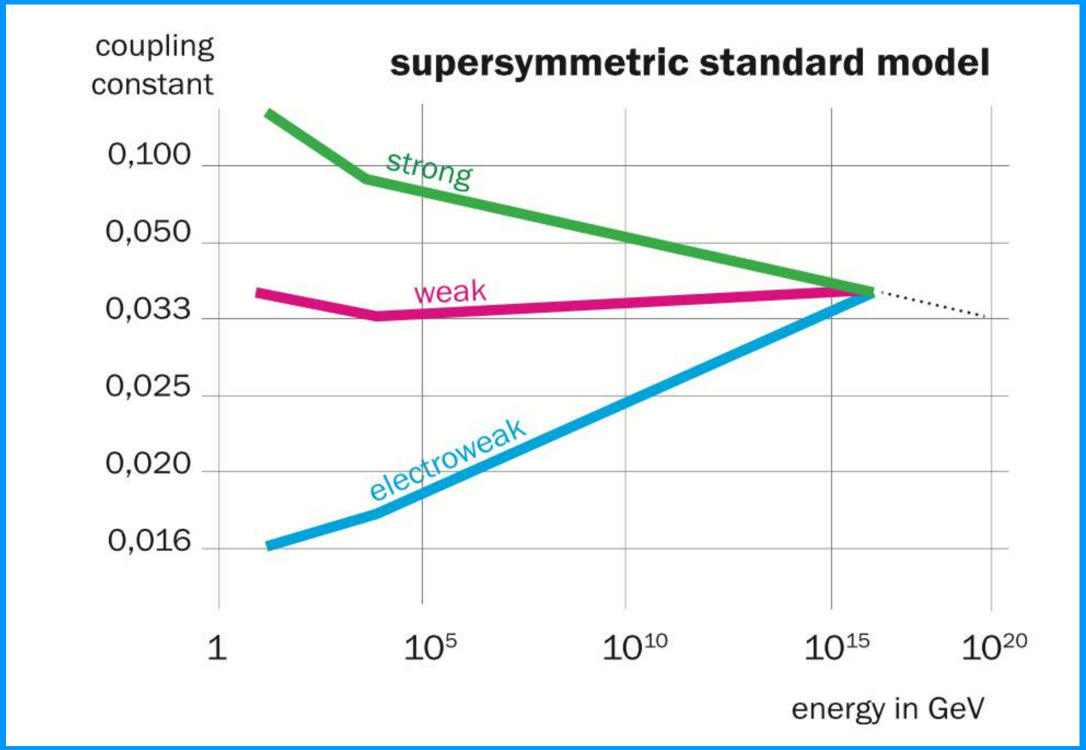
If SUSY particles exist with a mass ~1TeV, then the Higgs mass value and the universe become stable…WE HAVE OUR NATURAL UNIVERSE!

Unified in the name of SUSY

An extra bonus from the SUSY theory is that predicts precisely the **unification of electromagnetic week and strong forces** at a certain (very high) energy scale

Credits: Asimmetrie





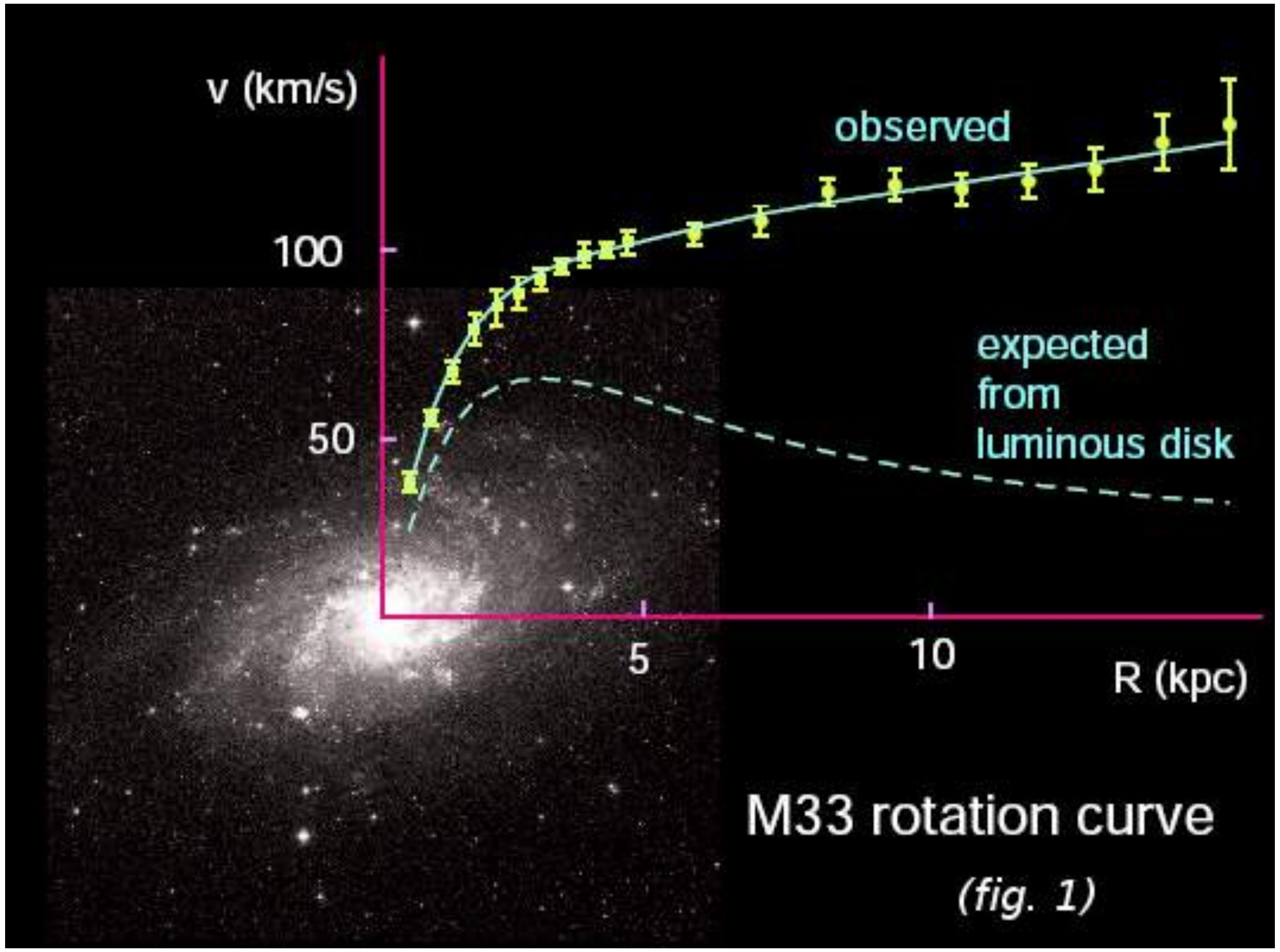
this is again very natural!

More "obscure" problems…

Measuring the velocity of stars at the edge of spiral galaxies we can predict their masses: since many years we know that the visible mass cannot justify what is observed

there's a lot of
DARK MATTER
in our universe

whose gravitational effects are however very much visible!



(fig. 1)

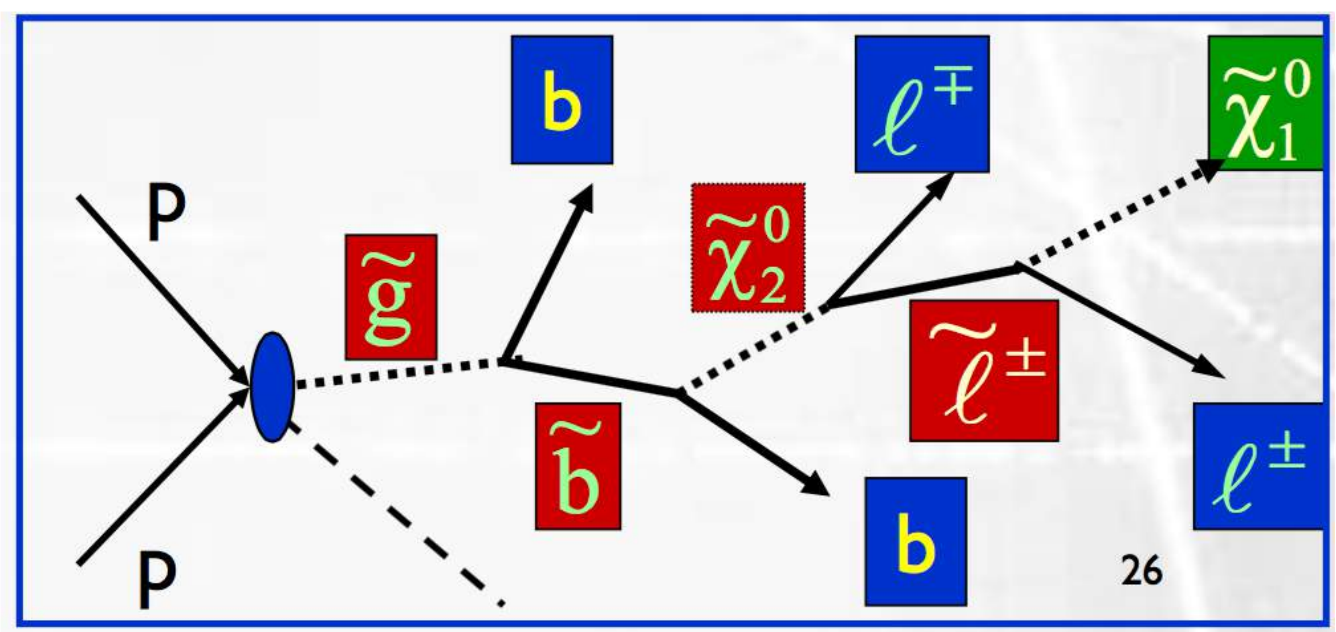
Actually, we do not understand most of the mass of the universe:

5% visible	23% dark matter	72% dark energy

...again SUSY to the rescue

Neutrino's with their tiny masses could explain the dark matter, but this solution has been discarded since it is not compatible with the evolution of the universe, as predicted from the study of the Cosmic Background Radiation: we need instead a Weakly Interacting Massive Particle (WIMP)

SUSY predicts the lightest s-particle (LSP) being stable (=cannot decay): being in the TeV range, **this is an excellent for the dark matter**



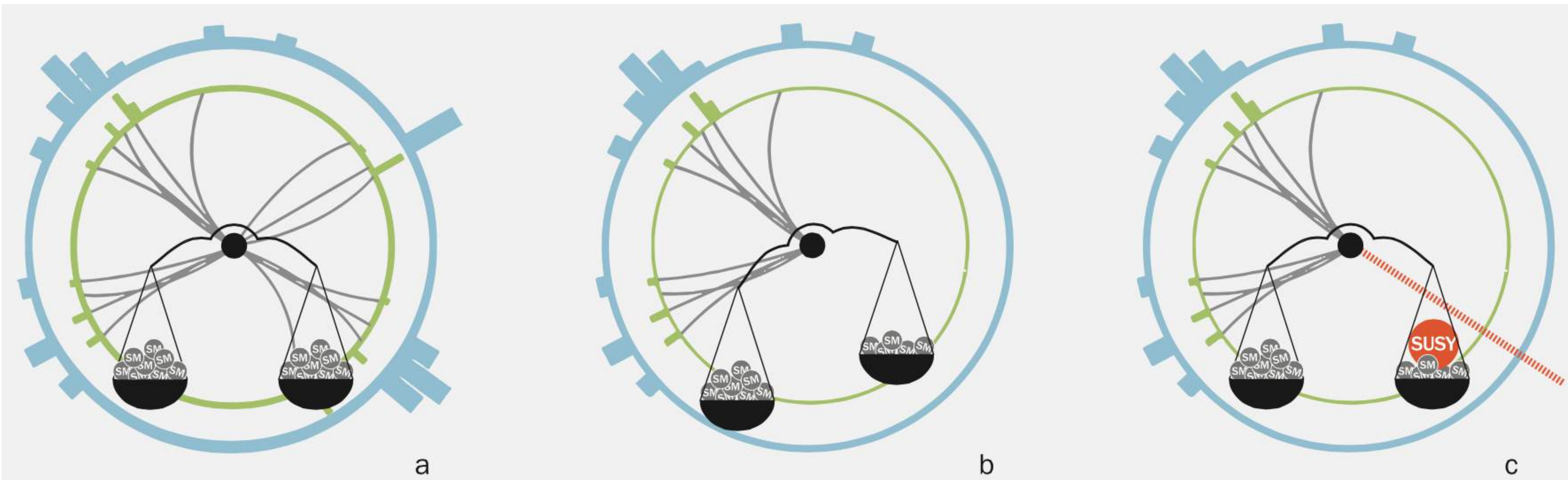
LSP!

Hopefully, we'll have soon an answer: if SUSY particles exist, we have to observe them at the LHC

Desperately seeking SUSY

If SUSY particles are created at LHC , they do not interact with the detectors and escape the observation: this is exactly what we hope to **"observe"**

Credits: Asimmetrie



SM particles only: energy is well balanced

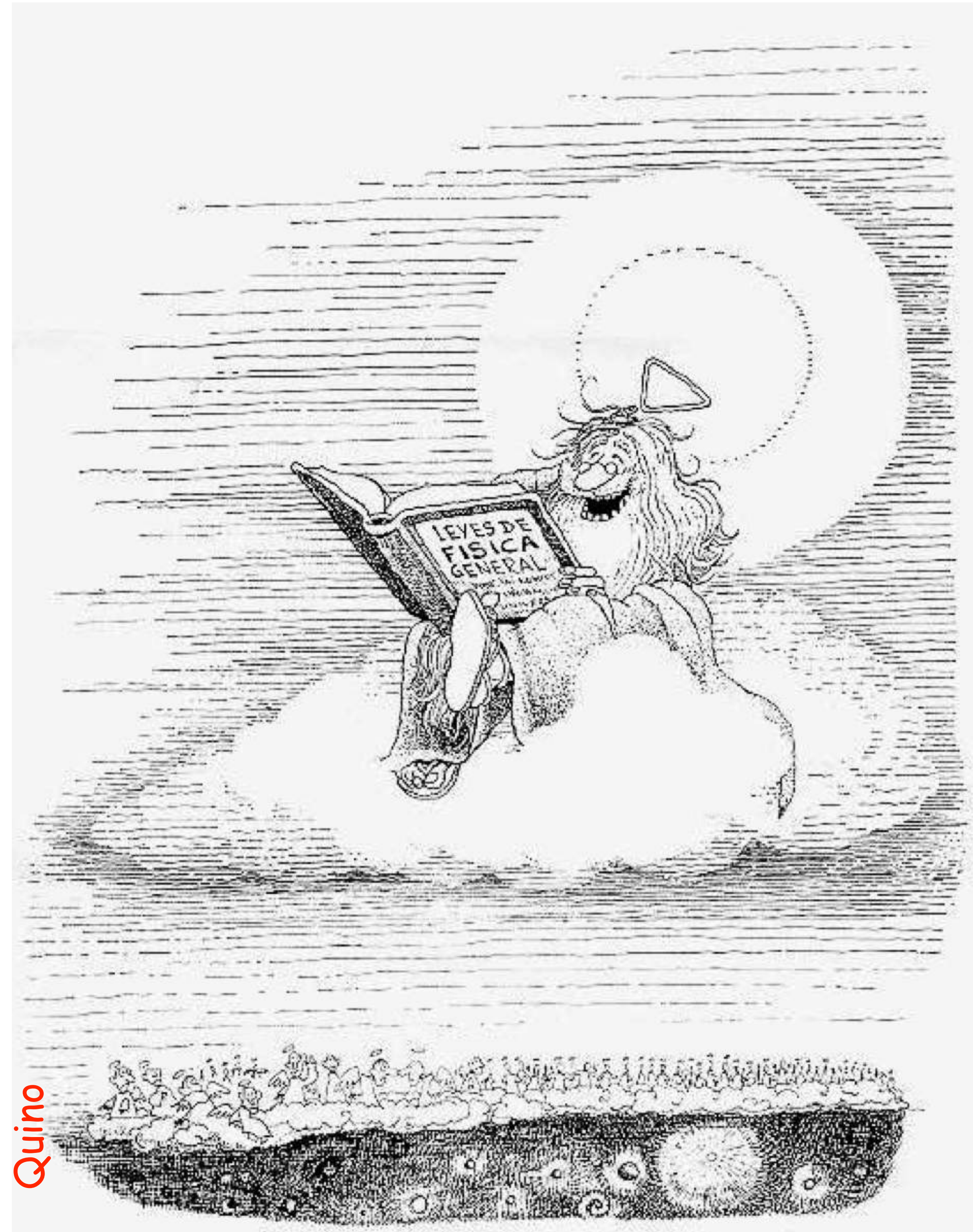
SM+SUSY particles: energy is unbalanced

Energy unbalance is explained by a SUSY particle escaping from our detector

Up to now, there's no sign of SUSY in LHC data: but new data are coming… exciting times are ahead of us!

But this can well be the conclusion!

Nature can of course have its own idea of "naturalness", very different from our…



Epilogue

LHC revealed the origin of the mass for the elementary particles: this was a great success of the Standard Model

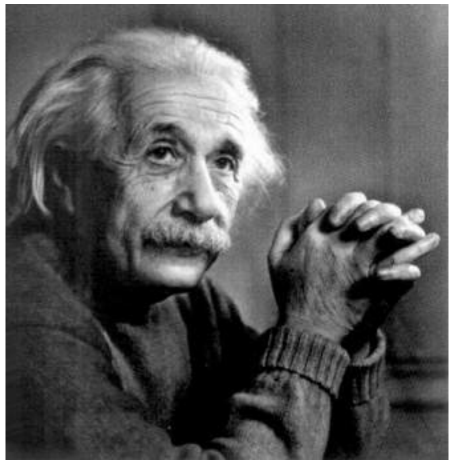
There're still many unsolved mysteries, which the Standard Model is not able to explain

- what is the origin of the dark matter and dark energy?
- where's the antimatter in our Universe?
- what is the origin of the mass scale between the different elementary particles? what is the origin of the neutrino masses?
- how to build a coherent picture for quantum gravity?

Many different scenario's have been proposed which could explain some of the above problems: the next years of experimentation at LHC will be crucial to open new windows in our understanding about the Universe

Epilogue

We're standing on giant's shoulders: the scientific revolution we're living now is the result of breakthroughs by visionary men, like



A. Einstein

W. Heisenberg

E. Fermi

P. Dirac

and many others…

Epilogue

But what makes science different is that we need experiments to connect "visions" with reality. This needs brilliant ideas, gigantic efforts, new technologies, strong determination of many people:

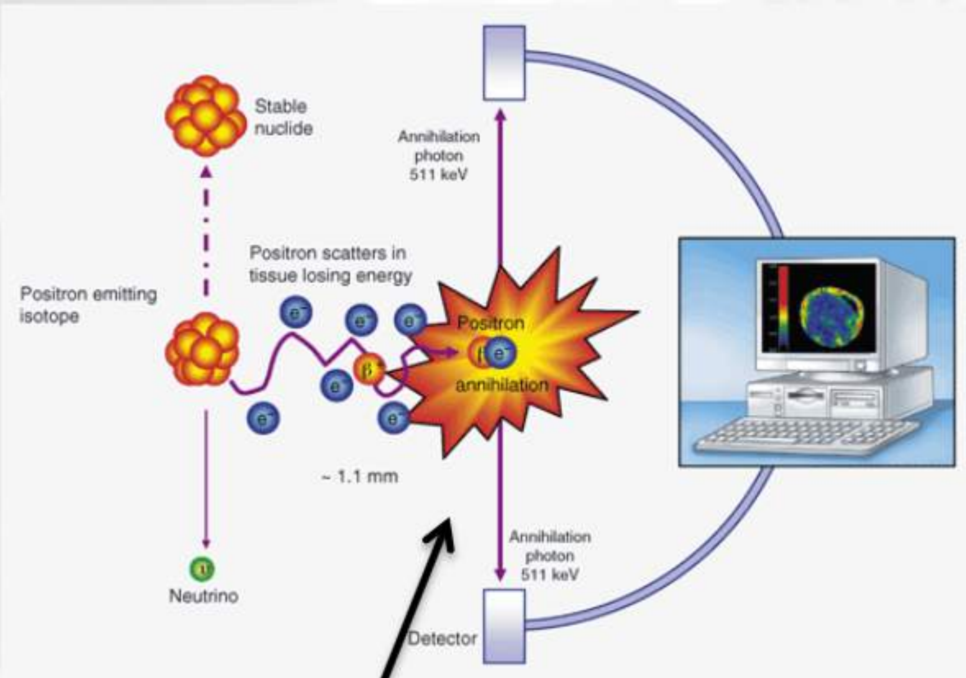
- 50 years to discover the Higgs boson
- 100 years to make the first direct observation of gravitational waves

There're still many unsolved mysteries in our Universe, and this brings me to the conclusion…

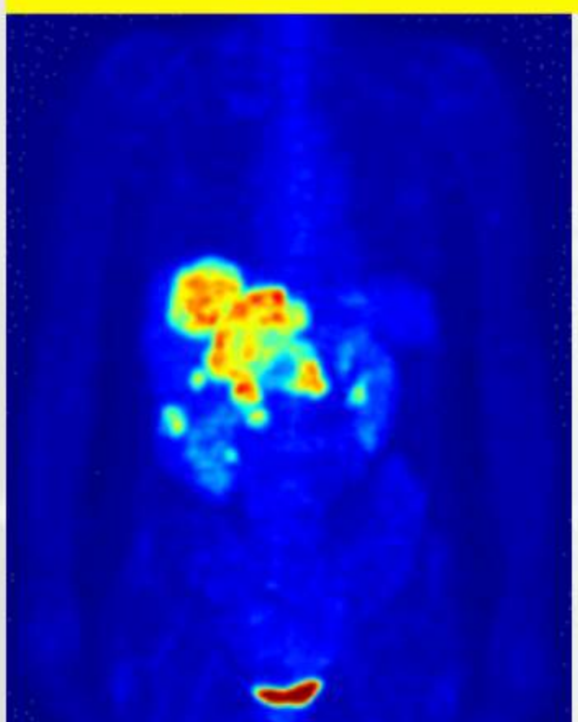
thanks for your attention!

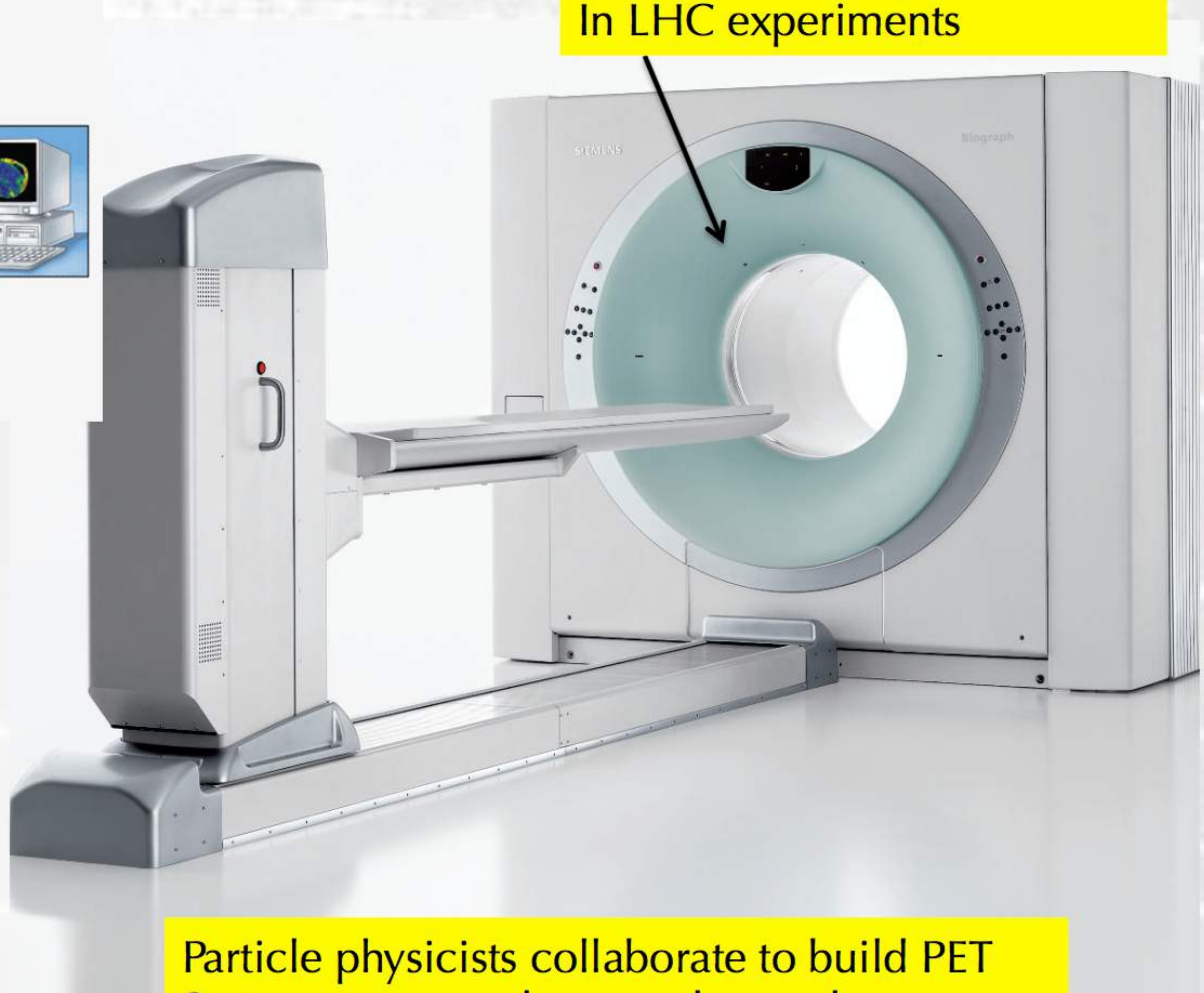
Supplementary material

Example no. 1
Positron Emission Tomography for early detection of cancer



Antimatter (positrons) at work !



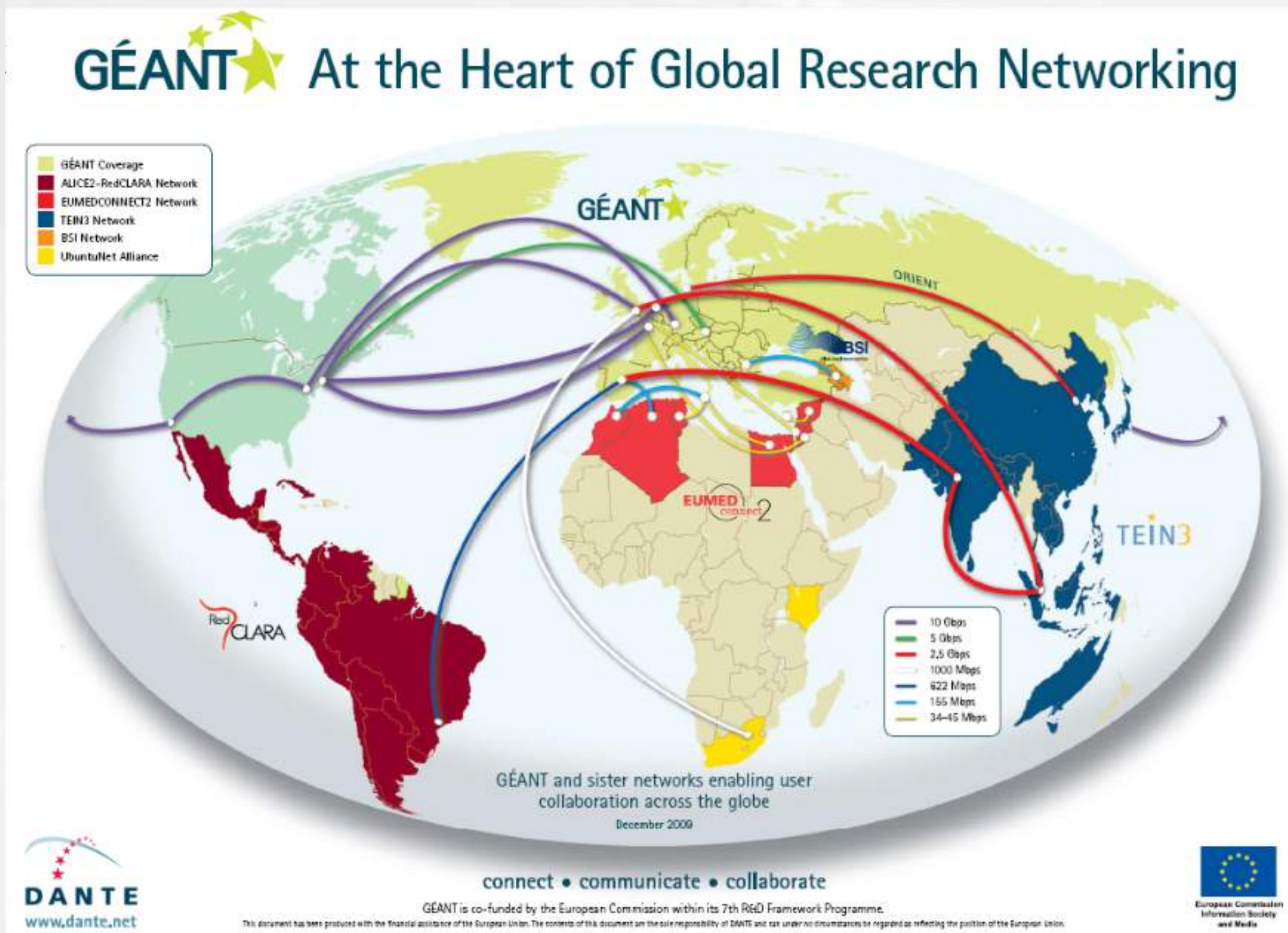


Here we have crystals used
In LHC experiments

Particle physicists collaborate to build PET
Systems more and more advanced

Example n. 2 – The World Wide Web

Web has born on August 6th, 1991. Tim Berners-Lee published online the first web page at CERN. At the beginning only used by physicists to exchange data, on April 30th 1993, CERN decided to open freely the access to the software.



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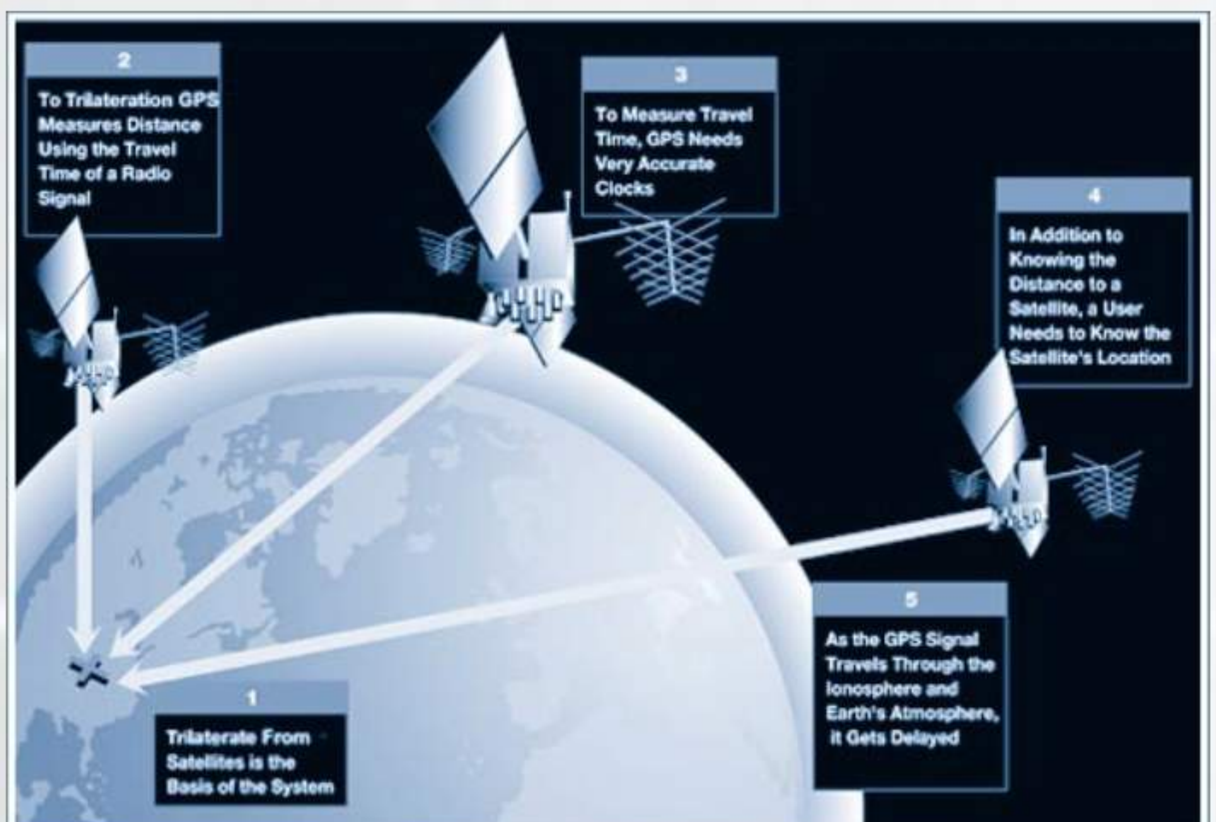
Example no. 3 – The GPS and Einstein's General Relativity

GPS satellites are orbiting around the Earth at a speed of 14,000 km/h.
Einstein's theory tells us that clocks slow down when are moving (the famous "twin paradox"): **- 7 μs each day**

GPS satellites are at an orbit of 20,000 km far from the Earth.
The gravitational force there is 4 times less strong than on the Earth and the clocks (due to Einstein's theory) accelerate: **+ 48 μs each day**

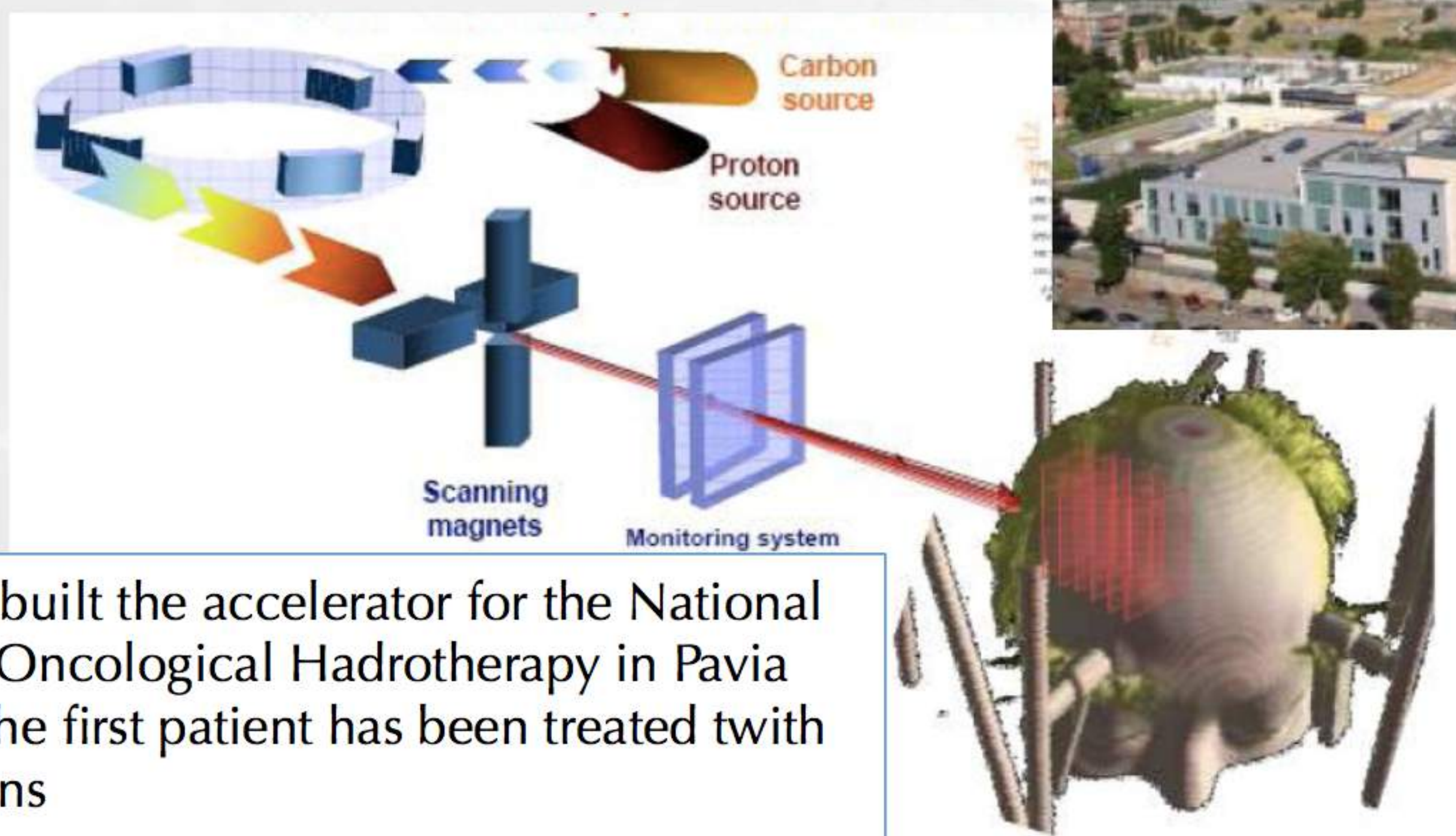
Total effect +35 μs → 11 km of error. Without the correction due to gravitational effects the GPS could not provide the current accuracy (**15 m error)**



Example no. 4 – Accelerators for cancer therapy

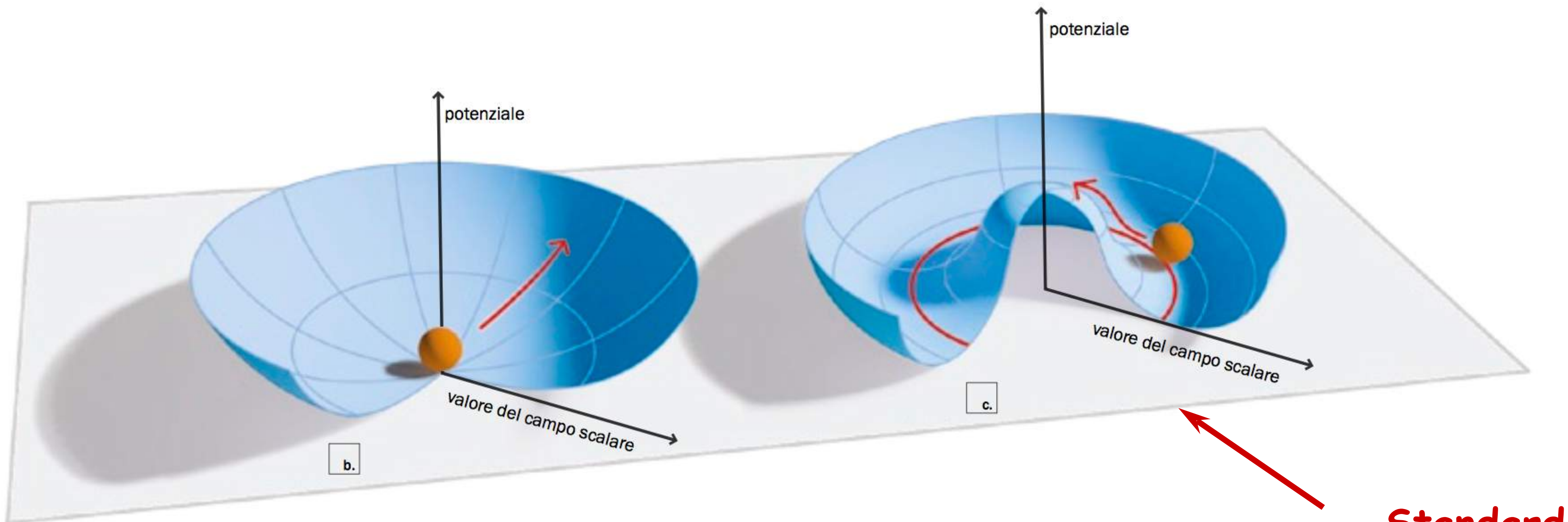
There are **26,000** accelerators installed in the world: **1% for research**, **44%** for radiotherapy, **55%** for industrial applications

A technological frontier is represented by **hadrotherapy**: destroy tumors in a more efficient way, hitting only damaged tissues and leaving untouched the rest of the body, especially in deep tumors, which are inaccessible.
Beams of **protons** or better of **ions** are sent very precisely on cancer tissue



INFN has built the accelerator for the National Centre of Oncological Hadrotherapy in Pavia
In 2012, the first patient has been treated twith Carbon ions

Higgs potential

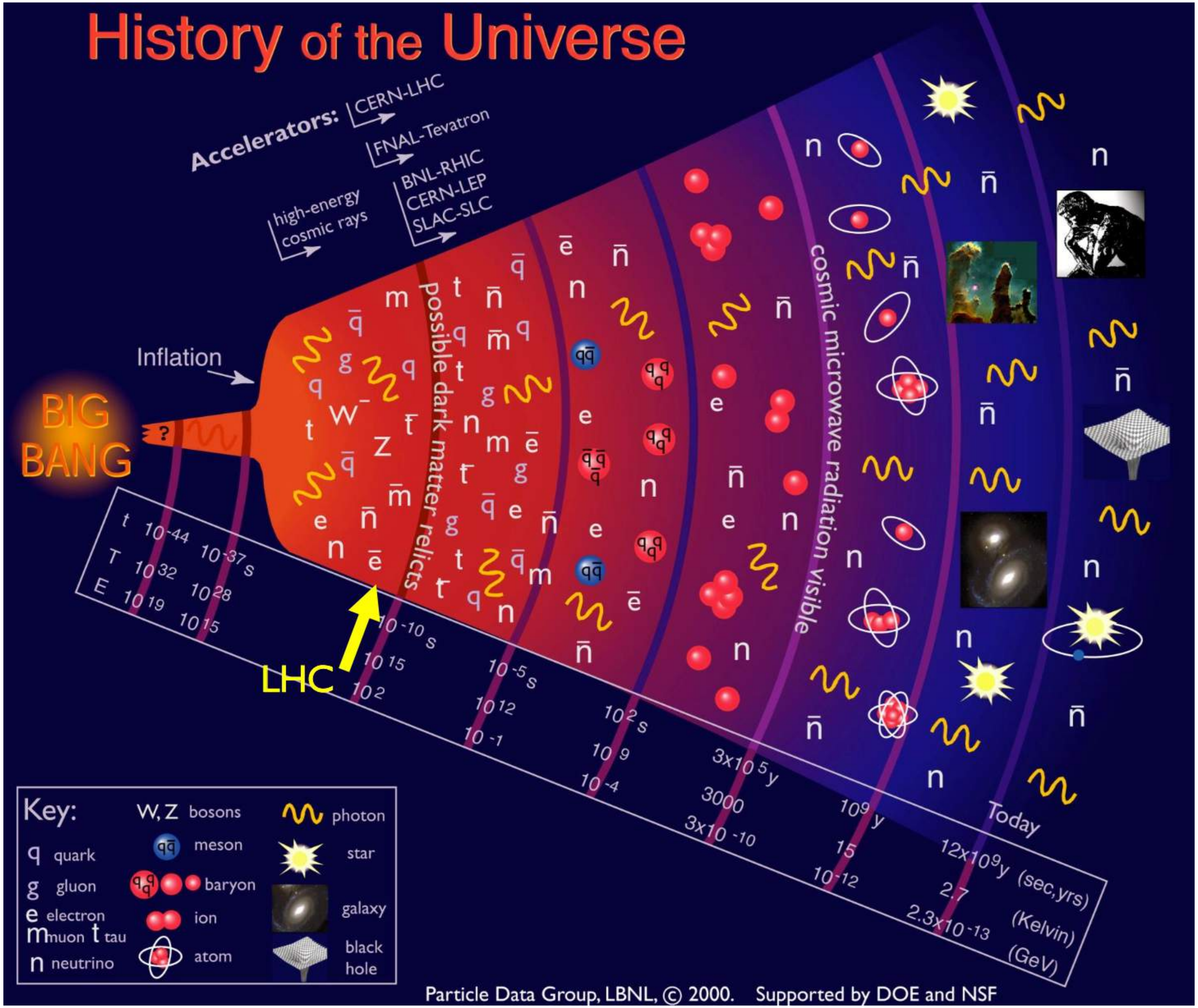


Standard Model

b.
Il potenziale a scodella gode di una perfetta simmetria per rotazioni attorno al suo asse. Inoltre, una pallina oscilla intorno al punto di equilibrio nello stesso modo indipendentemente dalla direzione della spinta iniziale.
Le oscillazioni attorno al minimo di potenziale corrispondono sempre a una particella con una certa massa perché hanno frequenza non nulla.

c.
Anche la forma a sombrero gode di una perfetta simmetria per rotazioni, ma presenta una rottura spontanea che porta alla comparsa di due particelle di massa diversa: quella dotata di massa corrisponde alle oscillazioni in direzione della salita, a frequenza non nulla; la particella priva di massa (il bosone di Goldstone) corrisponde invece alle oscillazioni a frequenza nulla lungo il fondo circolare, luogo di infiniti minimi equivalenti collegati da simmetria per rotazioni.

The history of the universe

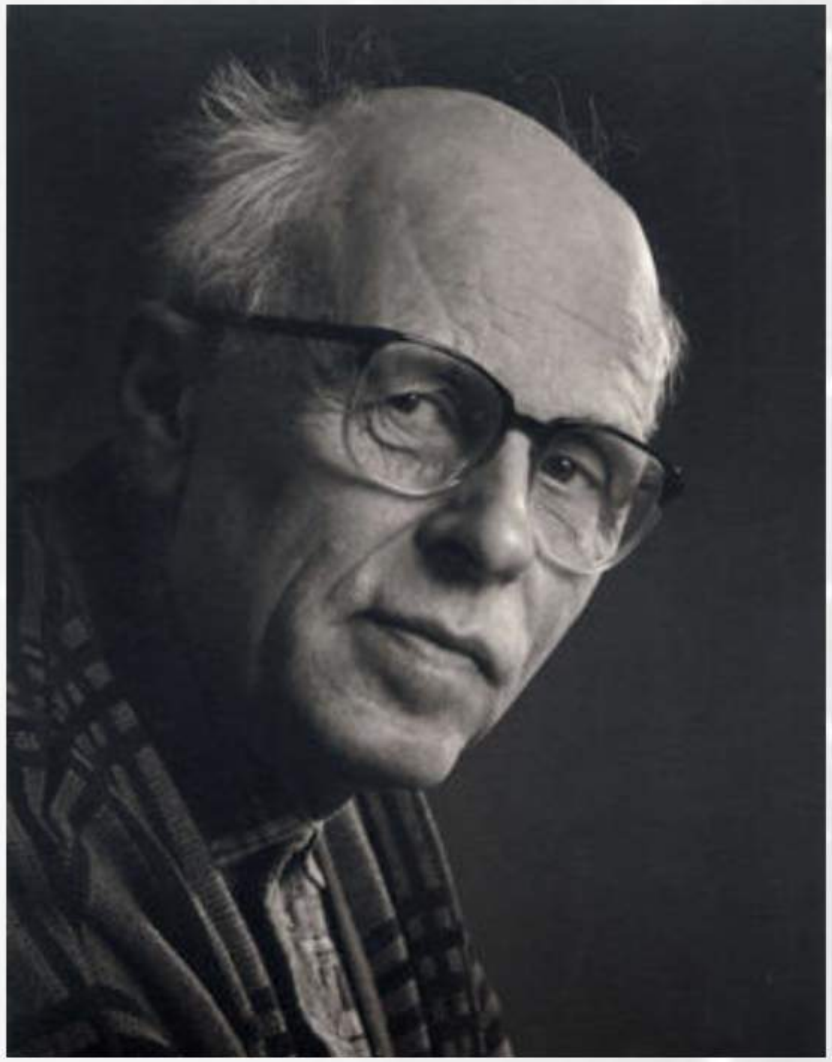


Matter vs Antimatter

Let's come back to the moment when the **inflation** (rapid expansion of the Universe) has finished: matter and anti-matter are in **equilibrium**

At that point a mechanism generates an asymmetry, and today we believe that it is the combination of various facts

In 1967 A. Sakharov (father of USSR atomic Bomb, political opponent and Peace Nobel Prize in 1975), made the hypothesis that 3 are the conditions for the start of baryogenesis (i.e. the victory of matter over antimatter):



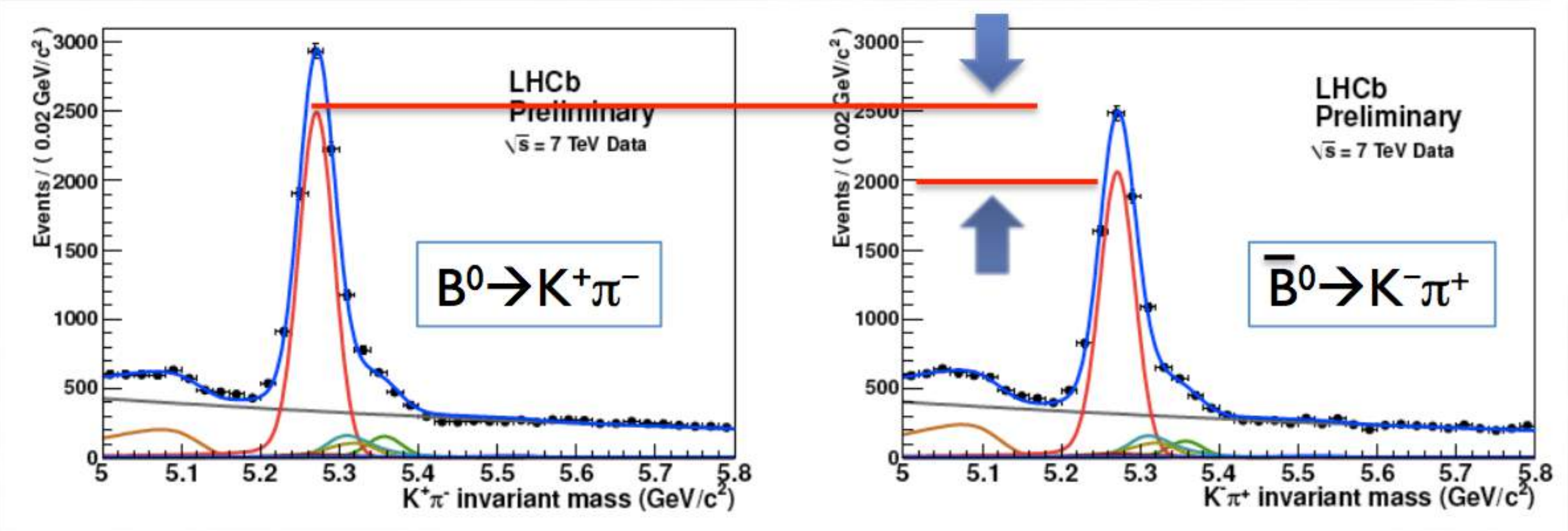
- **the violation of CP symmetry**
- **the possibility of creating baryons violating some conservation rules**
- **a system which is undergoing a rapid variation of state**

CP violation

In 1964, an experiment in the US discovered that the **CP symmetry** was violated in the decays of a special particle: **the neutral K meson**

Afterwards, the violation of CP has been observed (in 2000) also in neutral and charged **B mesons** (particles with a quark b inside) which are the ideal laboratory for studying matter anti-matter asymmetry

These particles are studied with large statistics and in detail in LHCb, as they are created in pp collisions, in particular in the forward direction
One way of measuring the asymmetry is to count "how many times" a neutral B or an anti-neutral B decays in a specific channel
The asymmetry can be seen "by eye" (**look to the red plot**)



Unfortunately, what we know now from K and B CP violation decays is that the amount of the effect is too small to explain the large effect needed to generate the asymmetry between matter and anti-matter
Therefore the search continues …

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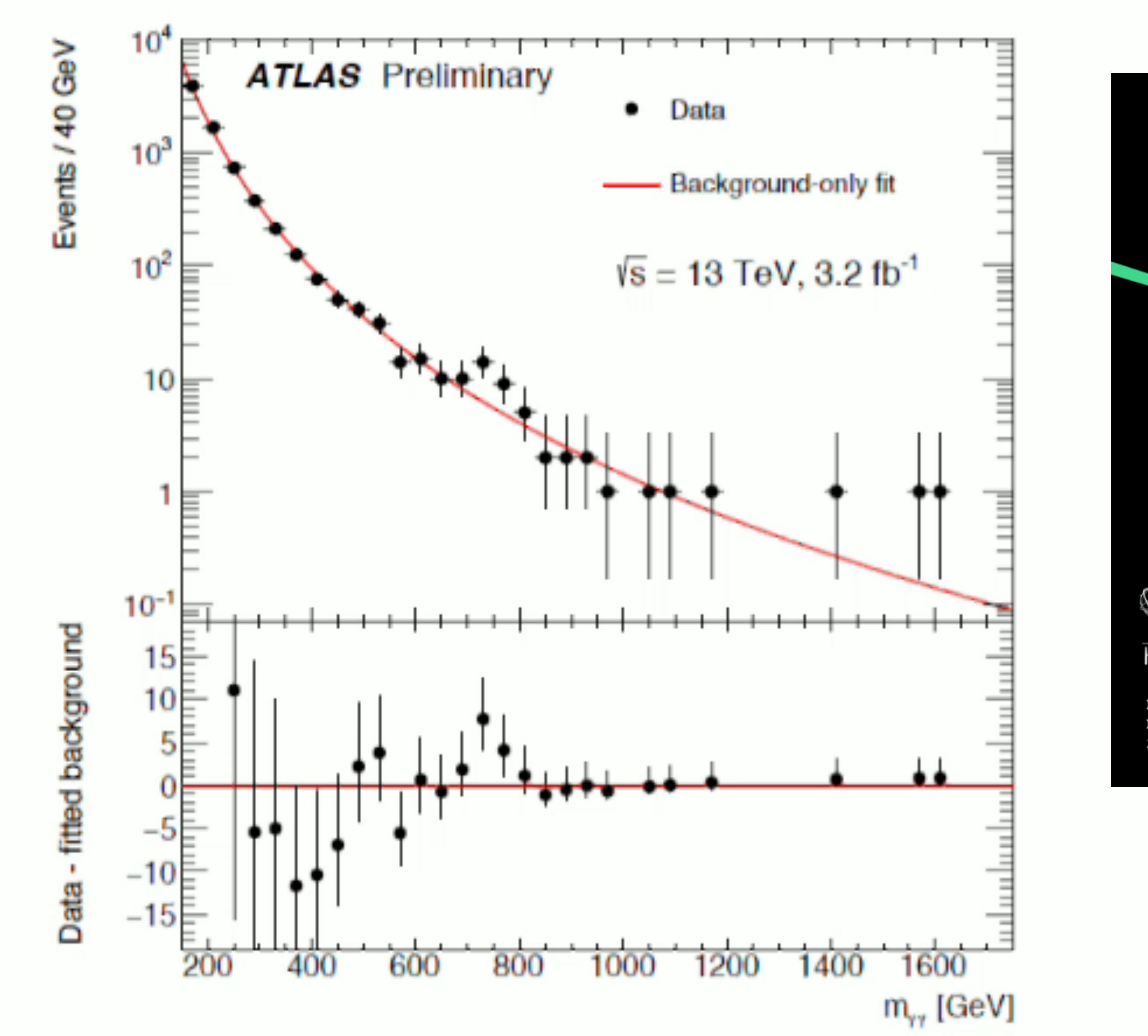
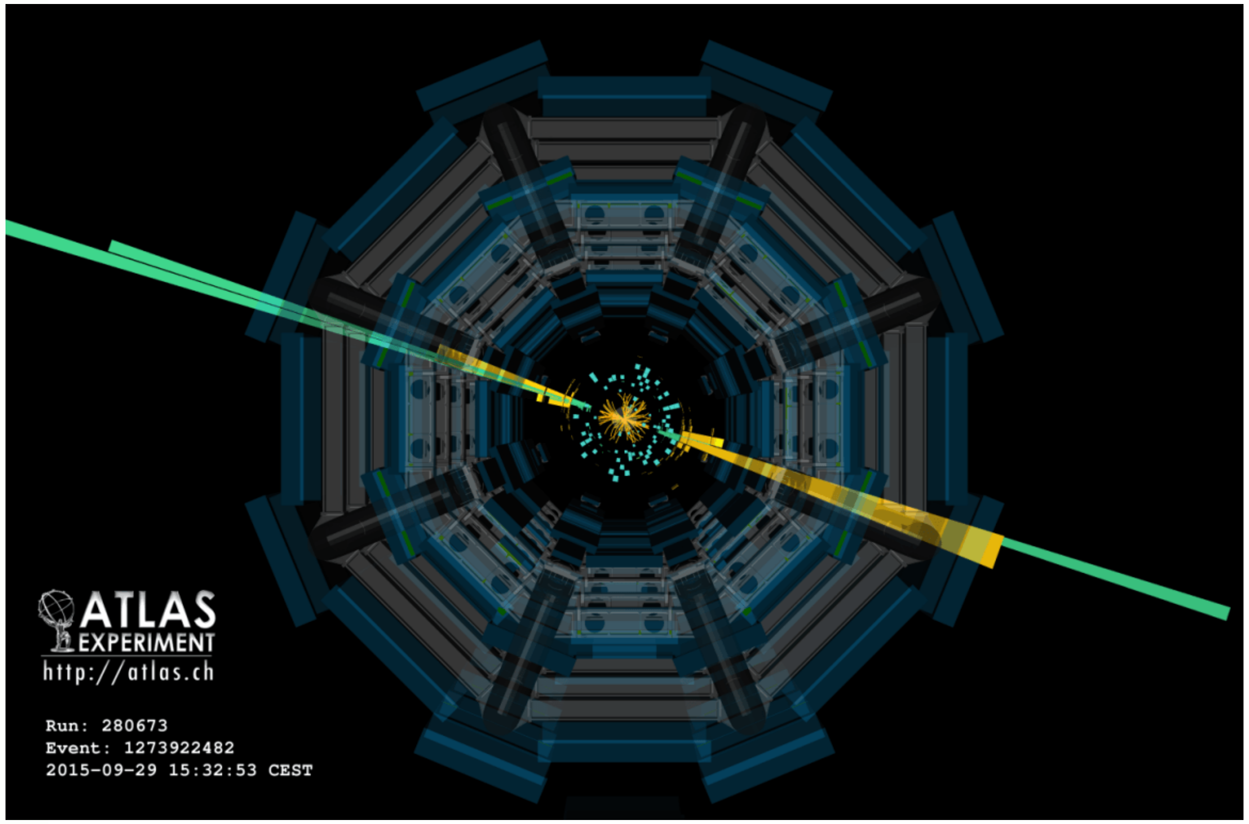
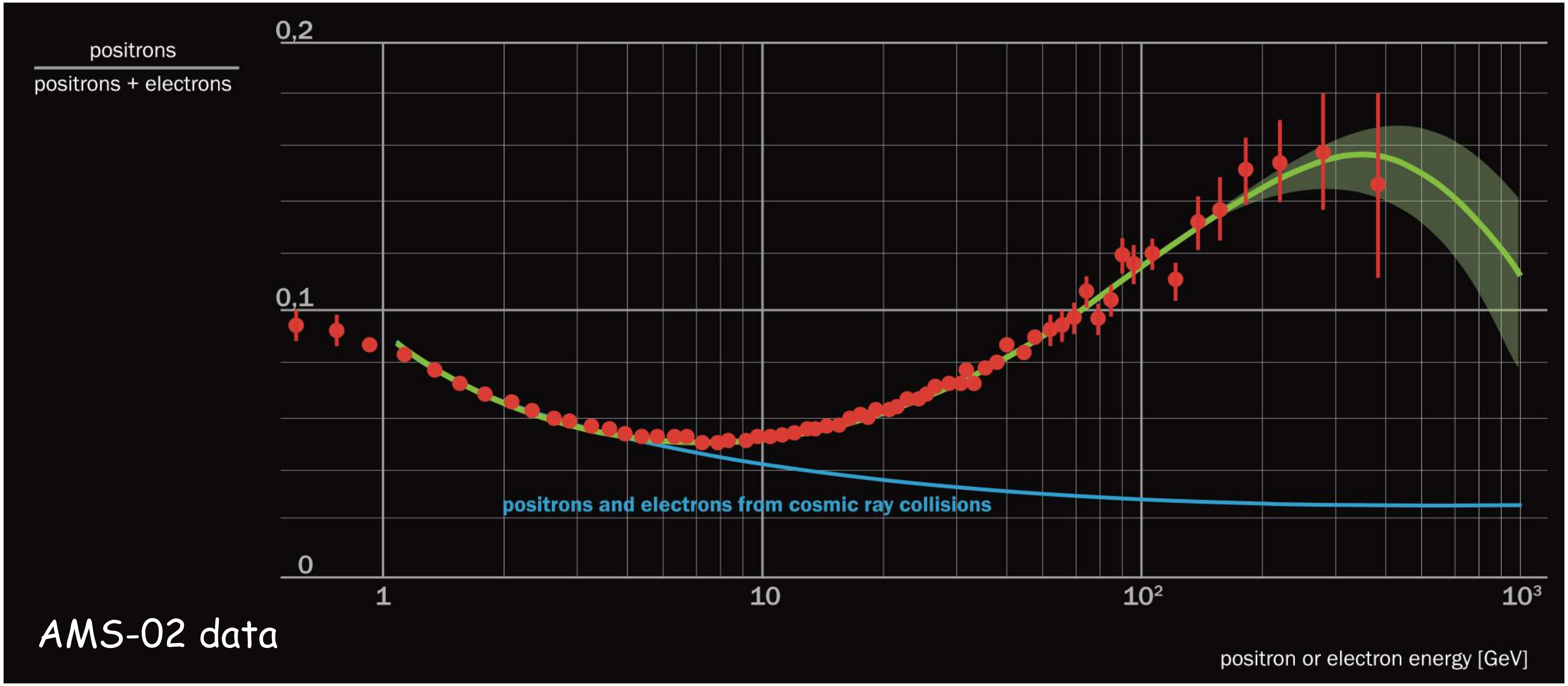
Something new at LHC?





Something new in the cosmic rays?

Credits: Asimmetrie

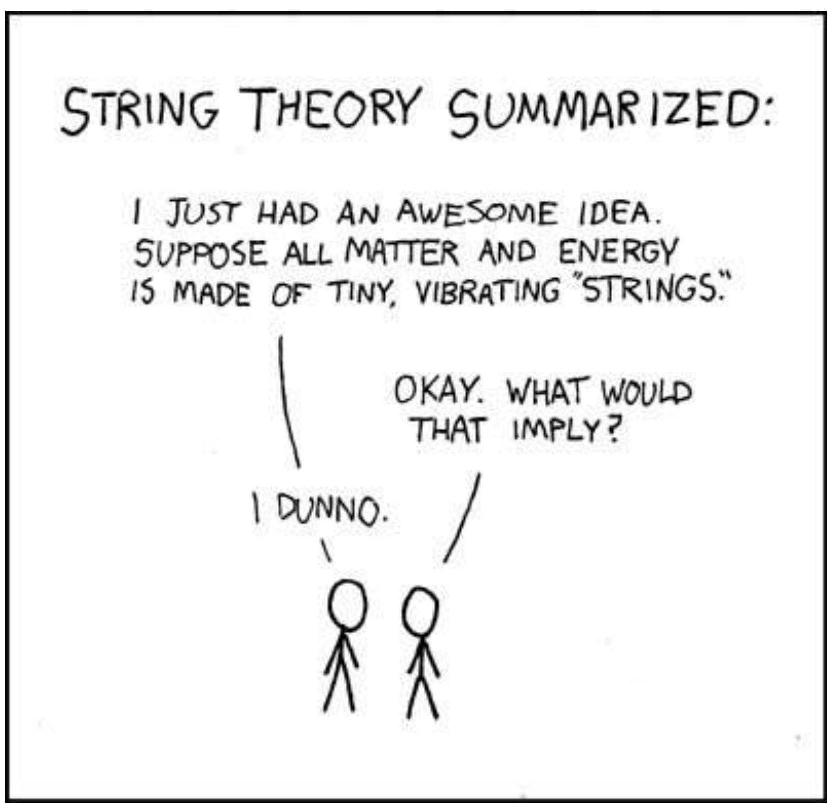


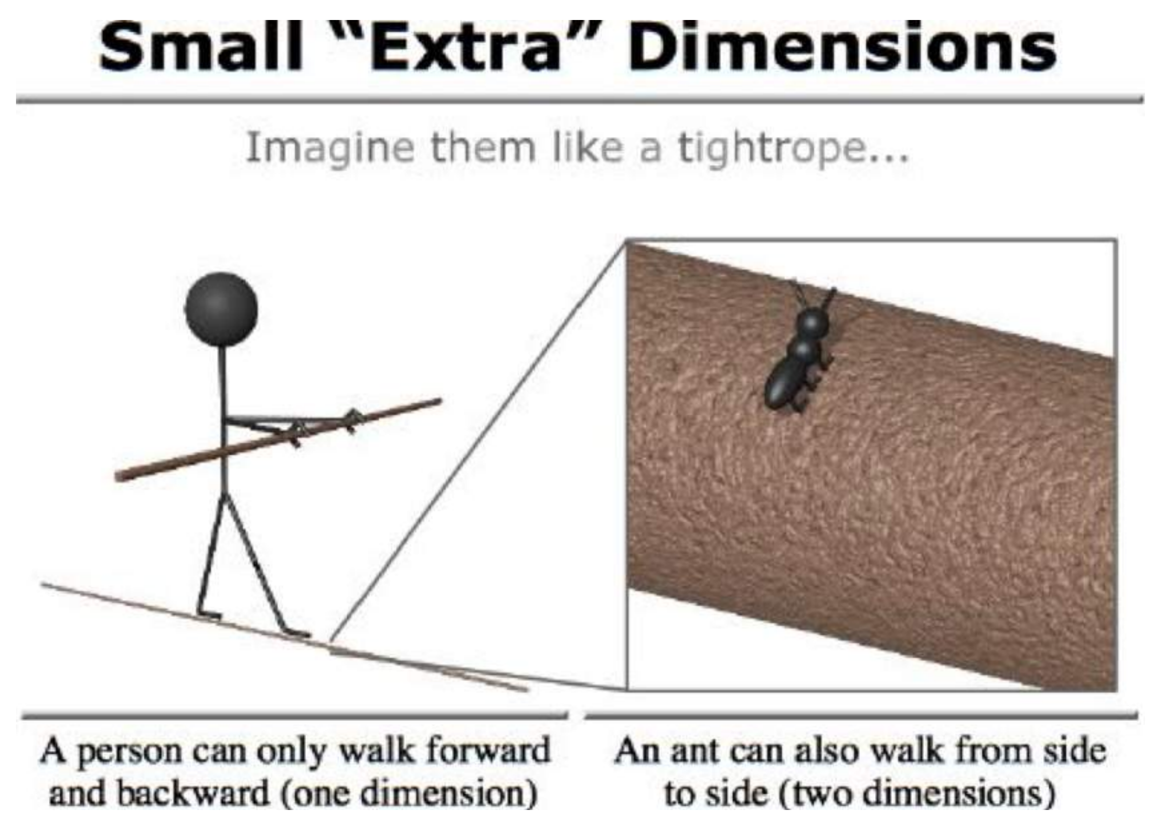
Collision of cosmic rays with the interstellar medium are expected to produce only one positron for every 10 electrons, and 1 antriproton for every 10,000 protons

String theories

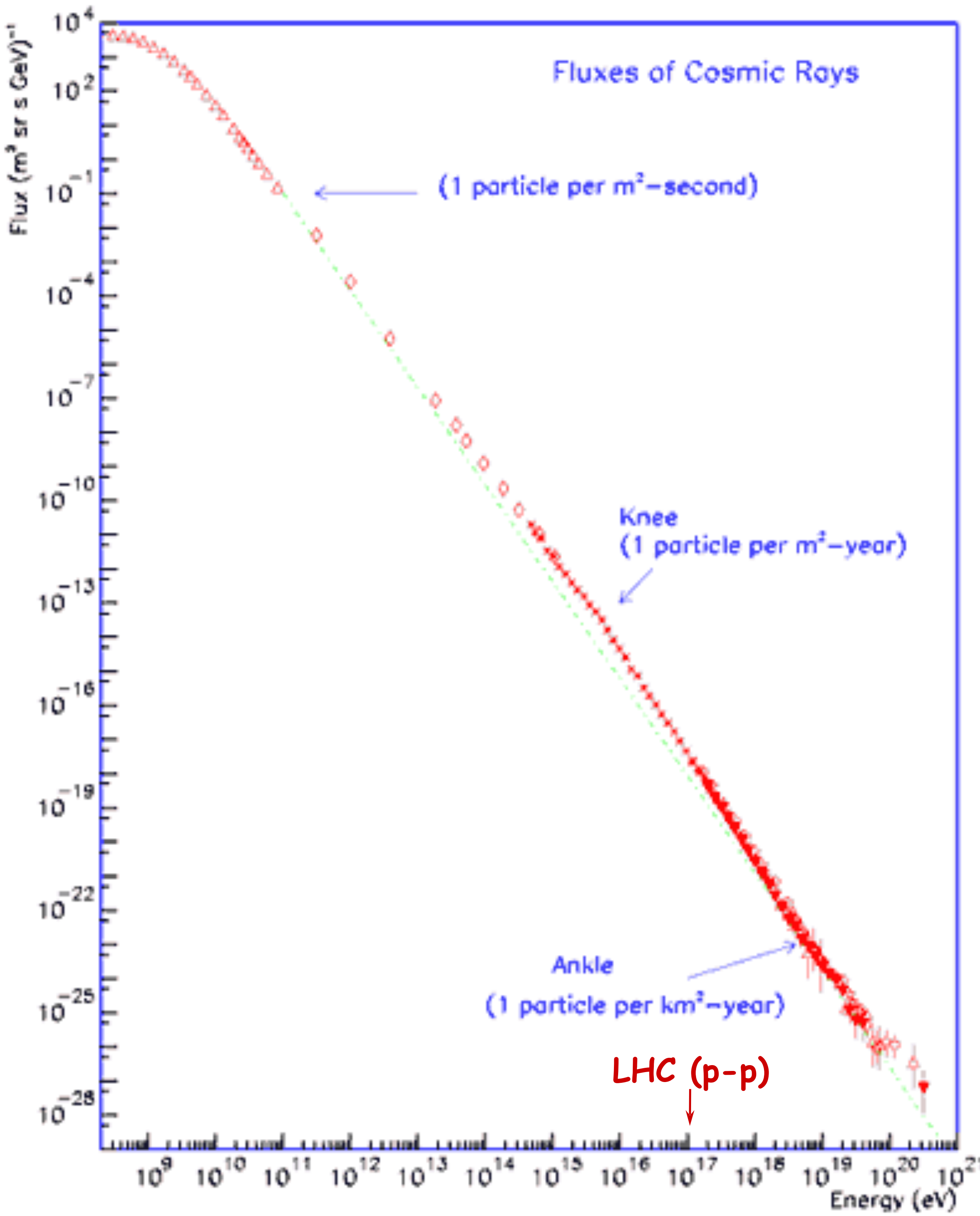
At the Planck energy scale, $M_P \sim 10^{19}$ GeV, the gravitational effects cannot be neglected at the quantum level. String theories implement such a scenario, by describing the elementary particles as tiny (order 10^{-33} cm) vibrating strings.

A "natural" consequence of these theories is the presence of extra-dimensions to the usual 3 space + 1 time: 10 space + 1 time ; the extra 7 space dimensions are confined on a length scale of $\sim 10^{-33}$ cm, and therefore they're only visible at the Planck energy scale.





Black holes at LHC?



In some string theory scenario's mini black holes (quantum black holes) could in principle be possible at the TeV energy scale, and therefore be produced in LHC collisions.

The same theories also predict that these black holes would evaporate instantaneously via emission of Hawking radiation, and the resulting emitted elementary particles could be visible in the LHC experiments

While the above phenomena being theoretical speculations, nevertheless there's a very strong argument which excludes any possibility for such black holes being dangerous for our life: very highly energetic (more than LHC) collisions occur in nature by cosmic rays:
- in 5 billion years $\mathbf{10^{22}}$ collisions/year on Earth above LHC energy
- In 10 years of LHC operation : $\mathbf{10^{17}}$ collisions

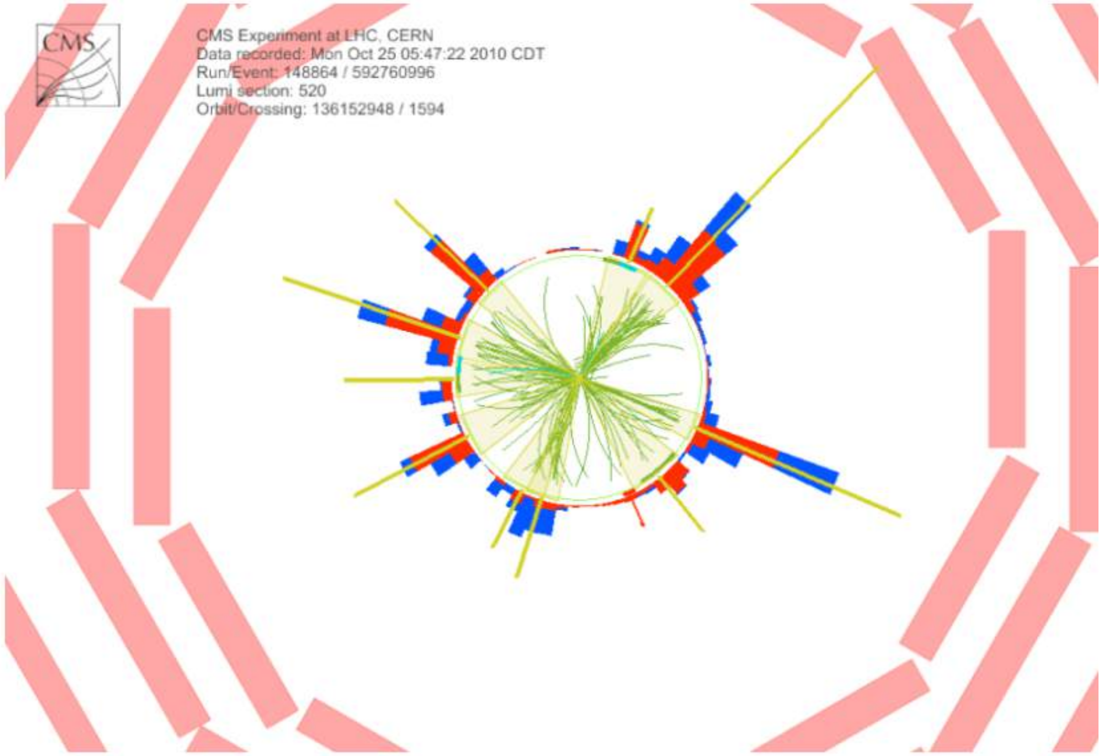
From the above we get Cosmic rays / LHC =$\mathbf{10^5}$, but if we add all the stars in our Galaxy we get $\mathbf{10^{36}}/10^{17}$=$\mathbf{10^{19}}$.

Black holes at LHC?

- Mini black holes produced at LHC would be light and tiny compared to cosmic black holes (~TeV versus ~3 Solar masses)
- This means they would be extremely hot (T~100 GeV) and evaporate almost instantaneously, mainly via Hawking radiation

- → cosmic BH 10^{19} GeV → LHC energy ~10^{4} GeV

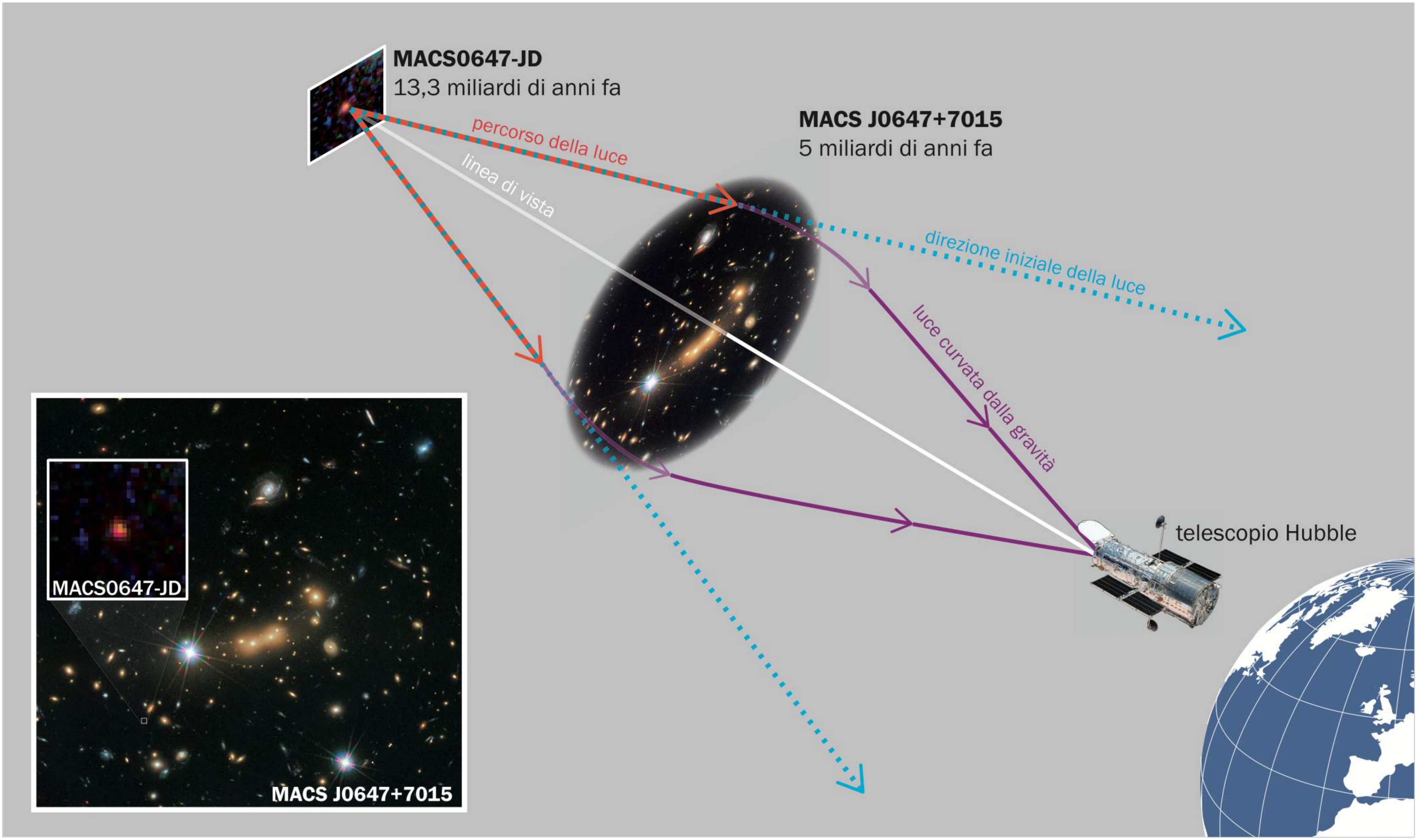
- Typical decay signature:
  ~6 ptc for each decay emitted spherically
    75% quarks and gluons
    10% charged leptons
    5% neutrinos
    5% of photons or W/Z boson
    new ptc around 100 GeV



BH event simulated by CMS

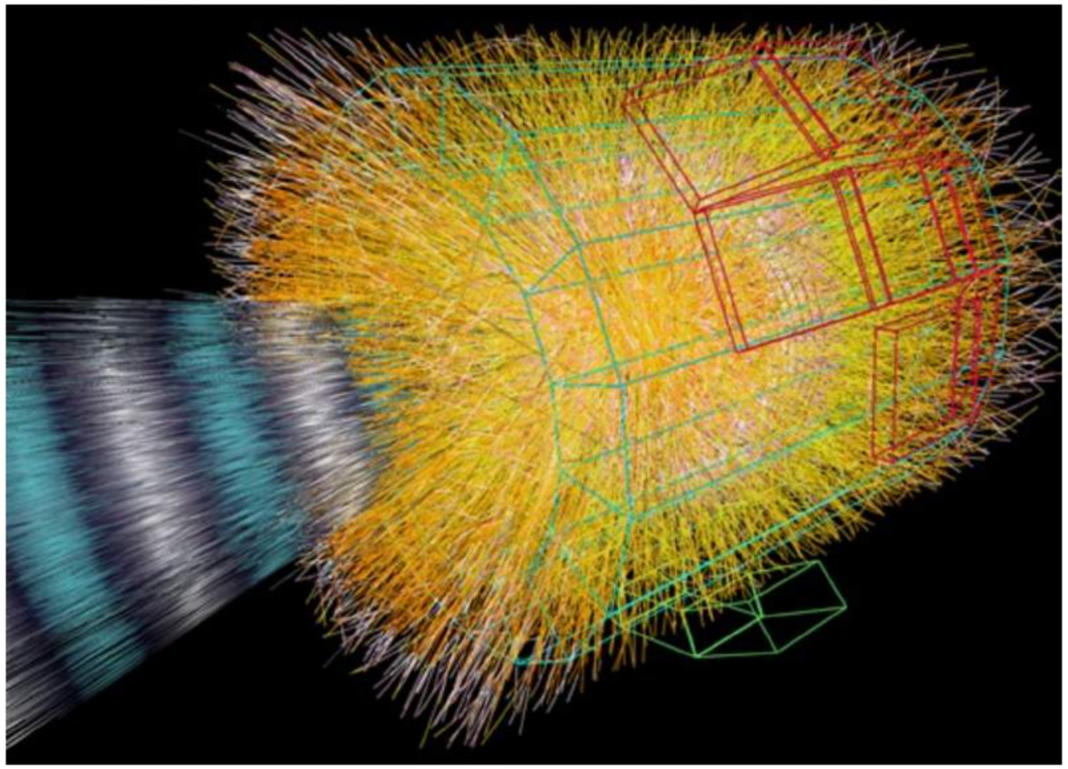
Gravitational lensing

Credits: Asimmetrie



Quark-gluon plasma

Pb+Pb event in Alice



For a few millionths of a second, shortly after the big bang, the universe was filled with an astonishingly hot, dense soup made of all kinds of particles moving at near light speed. This mixture was dominated by quarks and by gluons, carriers of the strong force that normally "glue" quarks together into familiar protons and neutrons and other species. In those first evanescent moments of extreme temperature, however, quarks and gluons were bound only weakly, free to move on their own in what's called a quark-gluon plasma.

To recreate conditions similar to those of the very early universe, LHC make head-on collisions between massive ions, such as lead nuclei (A=207, Z=82). In these heavy-ion collisions the hundreds of protons and neutrons in two such nuclei smash into one another at energies of upwards of a few TeV each. This forms a miniscule fireball in which everything "melts" into a quark-gluon plasma.

The fireball instantly cools, and the individual quarks and gluons recombine into a blizzard of ordinary matter that speeds away in all directions. The debris contains particles such as pions and kaons, which are made of a quark and an antiquark; protons and neutrons, made of three quarks; and even copious antiprotons and antineutrons, which may combine to form the nuclei of antiatoms as heavy as helium. Much can be learned by studying the distribution and energy of this debris. An early discovery was that the quark-gluon plasma behaves more like a perfect fluid with small viscosity than like a gas, as many researchers had expected.