The Large Hadron Collider & Particle Physics

Souvik Das

CERN – European Centre for Nuclear Research

CERN – European Centre for Nuclear Research

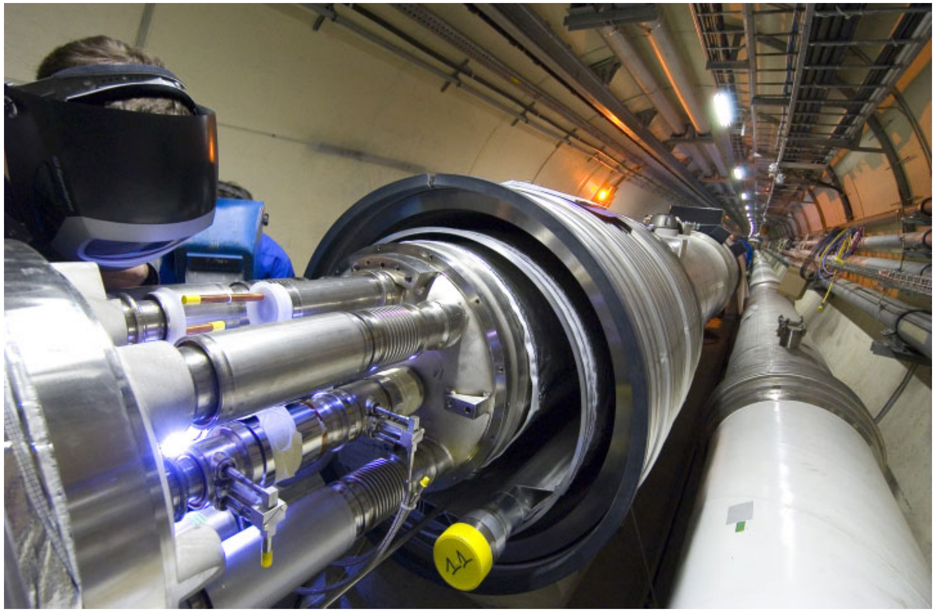
lies the world's fastest and most brutal racetrack…

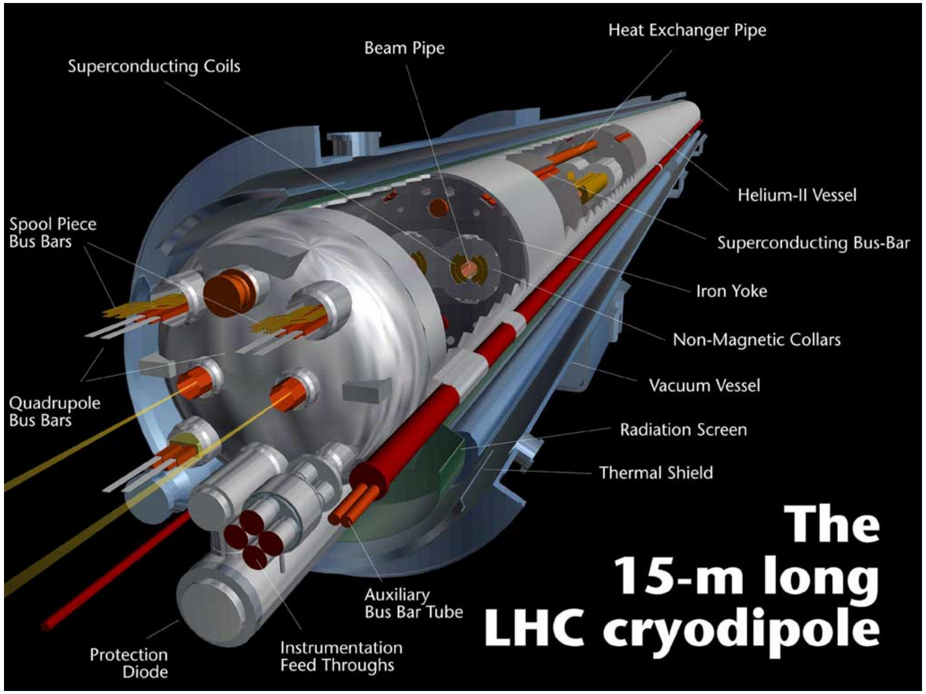
Protons race around a 27 km circuit at **99.999999%** the speed of light,

crashing head on into each other **40,000,000** times a second.

CERN – European Centre for Nuclear Research

in the **emptiest** space in our solar system…





The beam pipe is evacuated to the same vacuum as interplanetary space. 10^{-13} atmospheres.

The pressure is about $1/10^{th}$ that of the surface of the moon.

CERN – European Centre for Nuclear Research

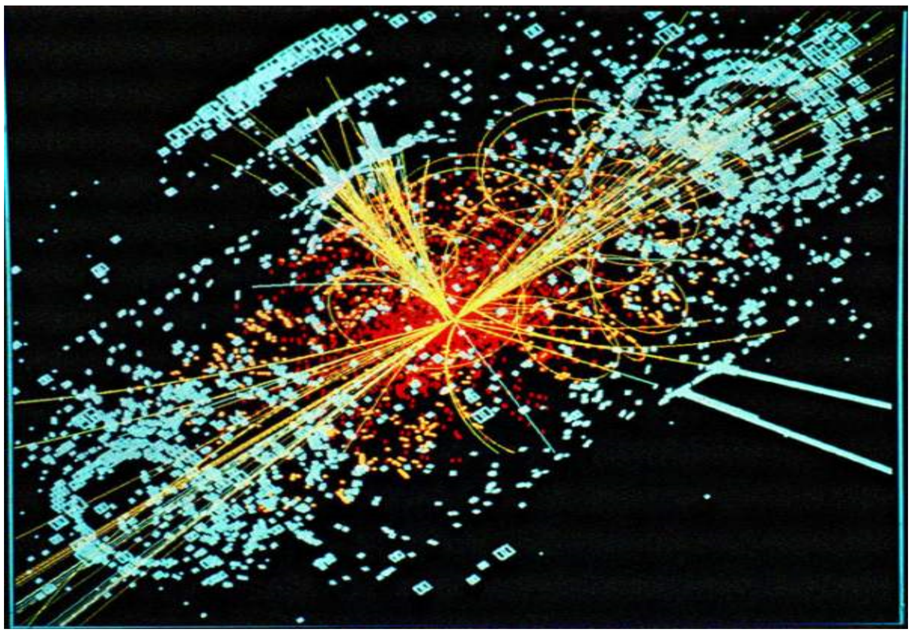
in one of the **coldest** regions in the universe…

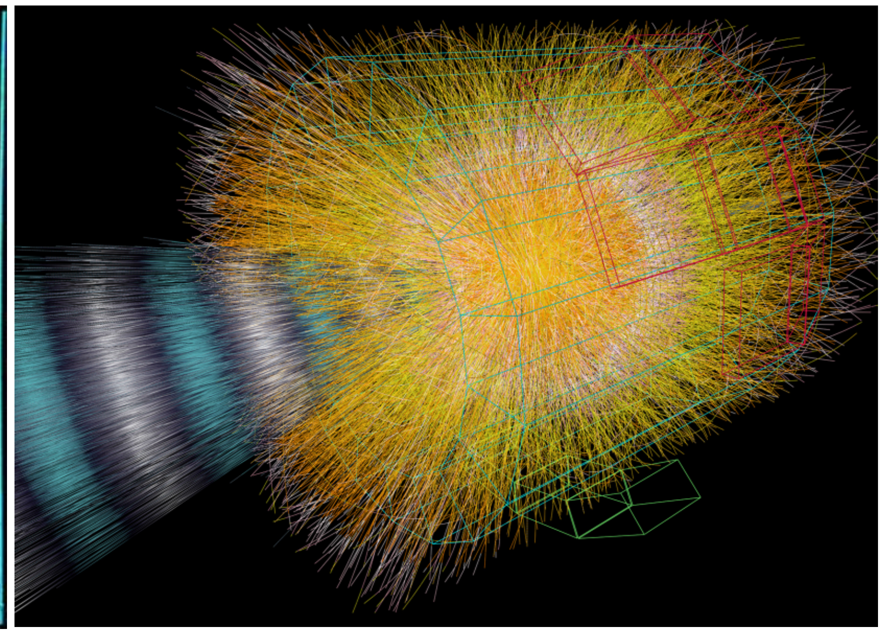
Superconducting and superfluid liquid helium is maintained at -271.3 C or 1.9 K.

That is a little colder than interstellar space.

CERN – European Centre for Nuclear Research

will occur some of the **hottest** reactions in our galaxy…



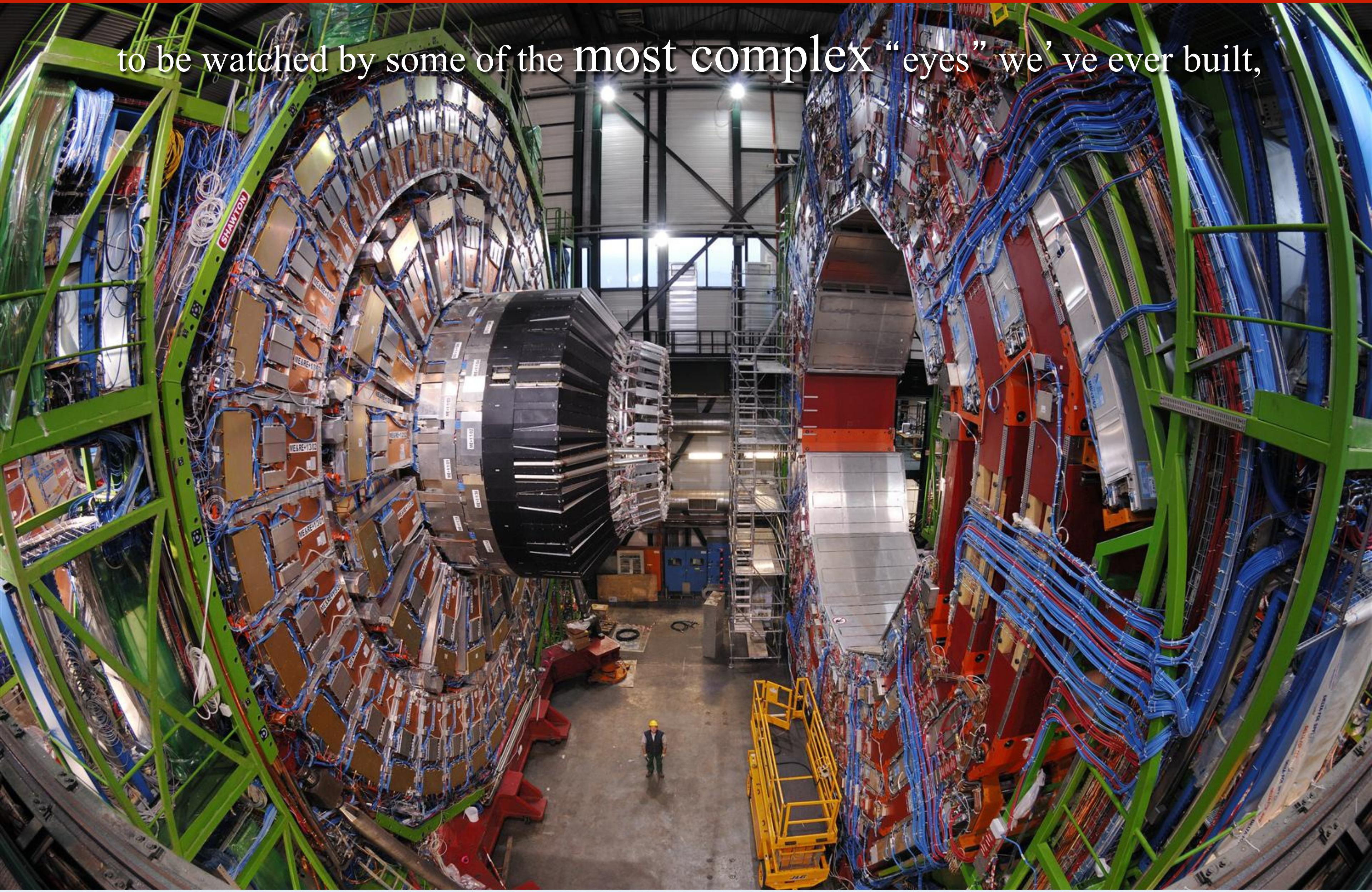


Violent collisions corresponding to temperatures a billion times higher than the core of the sun will be produced.

That is roughly 160,000,000,000,000,000 C

CERN – European Centre for Nuclear Research

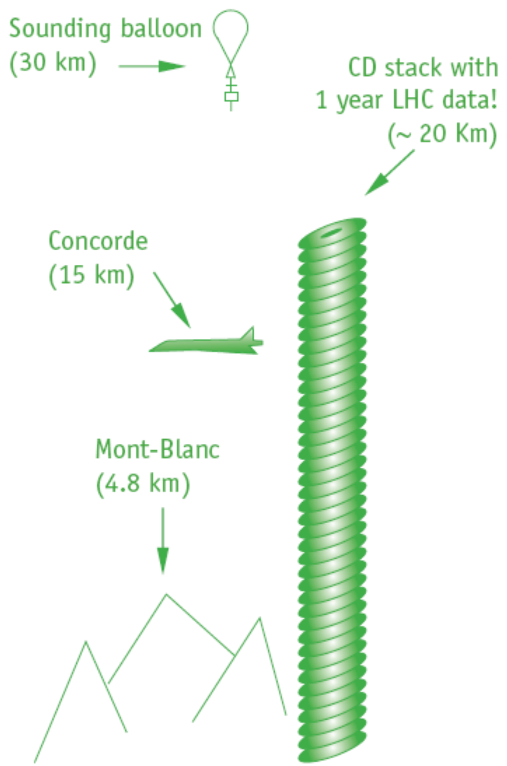
to be watched by some of the **most complex** “eyes” we’ ve ever built,



The detectors together have 140 million data channels observing at 40 million times a second.

CERN – European Centre for Nuclear Research

and analyzed by the most **powerful** computing system in the world.



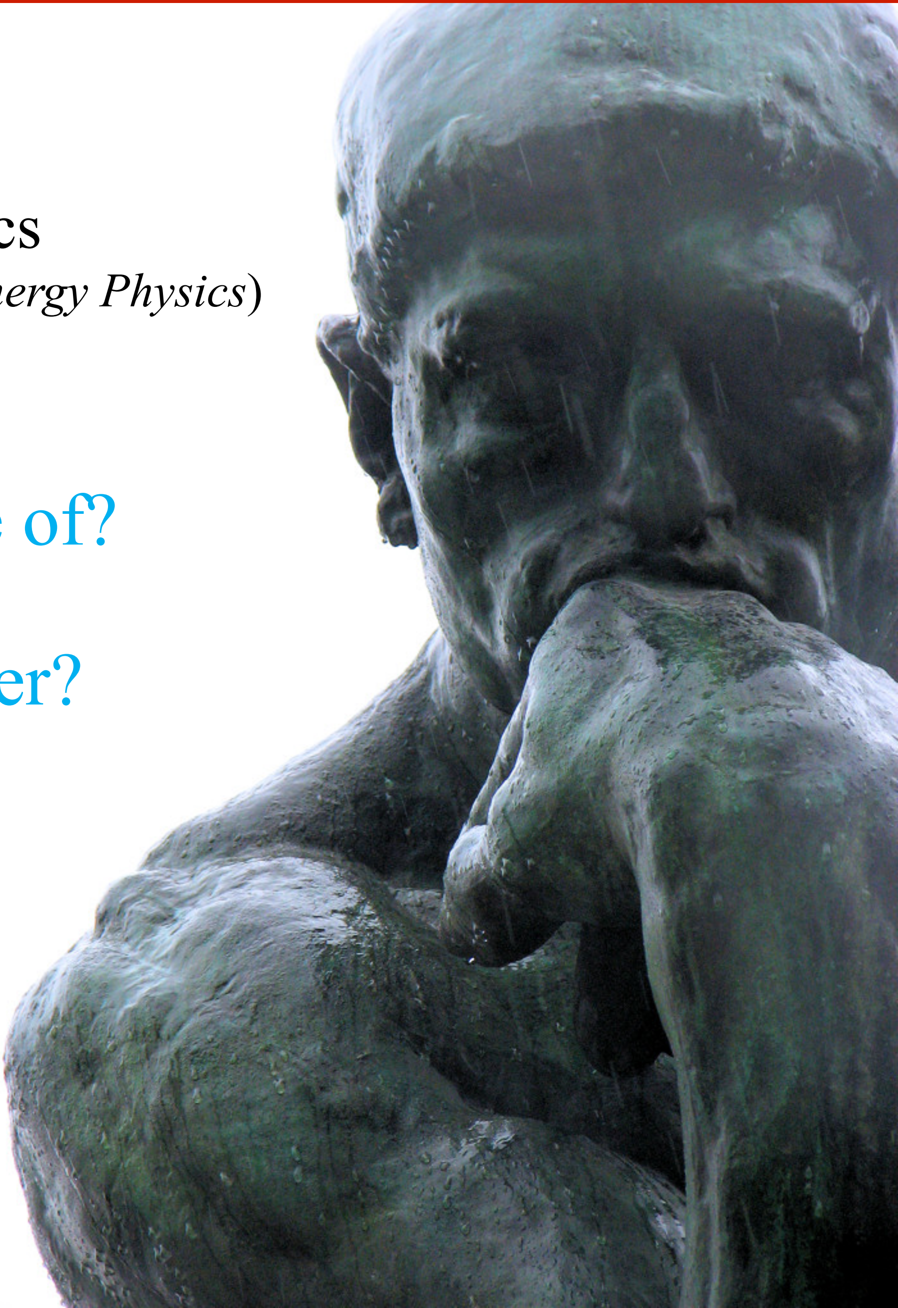
The detectors will spew out analyzed data at **700 MB/sec.**

That is ~30,000 Encyclopedia Britannicas *every second*!

That is 15,000,000 GB (15 PB) per year

20 km stack of average CDs per year.

Why?



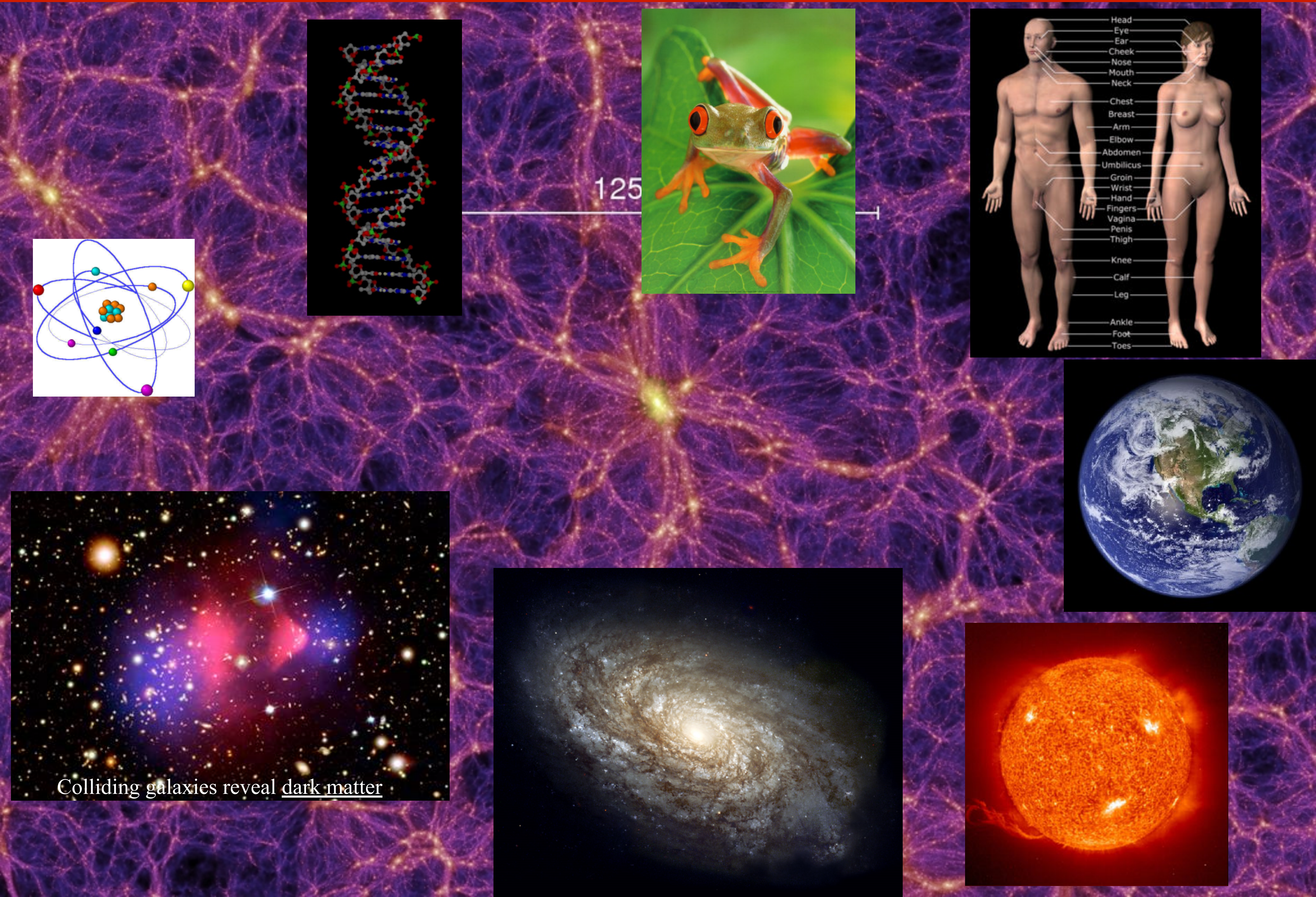
The Aim of Particle Physics

(a.k.a *Elementary Particle Physics*, or *High Energy Physics*)

1. What is everything made of?

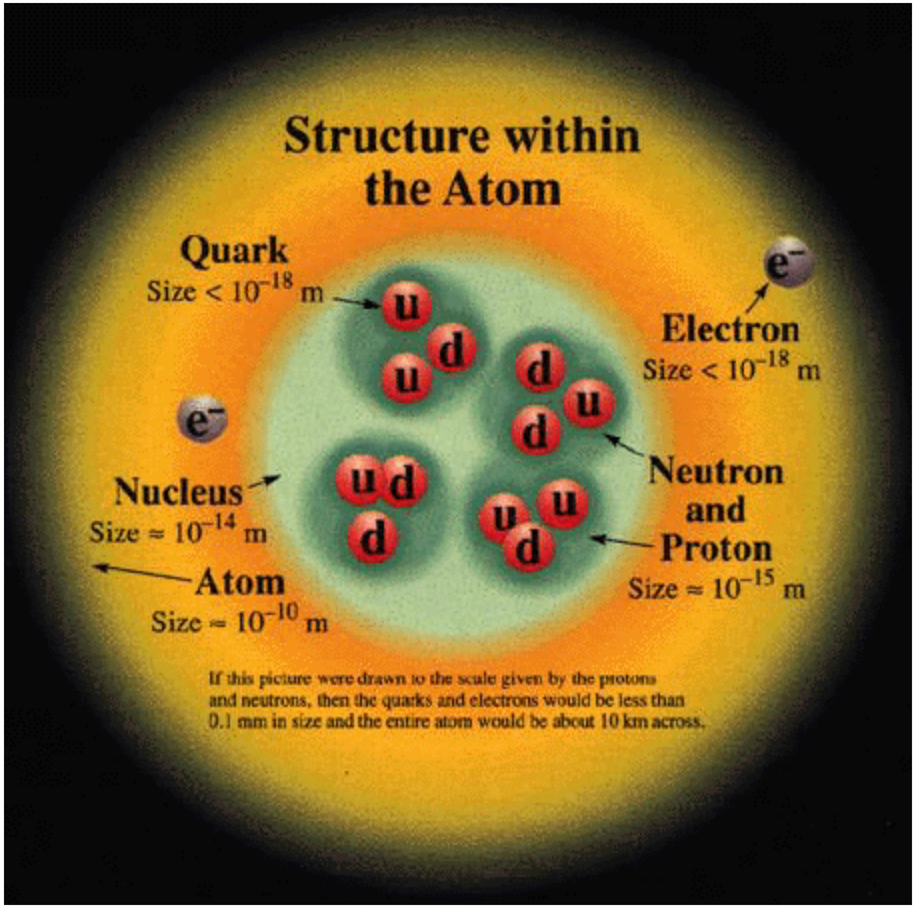
2. What holds it all together?

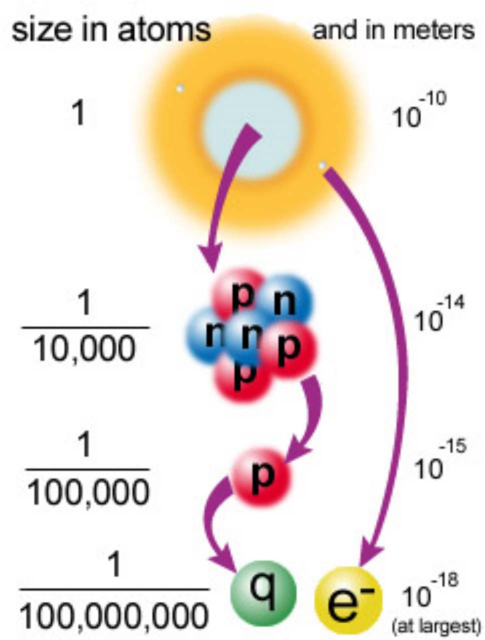
What is everything made of?



Colliding galaxies reveal dark matter

What is everything made of?



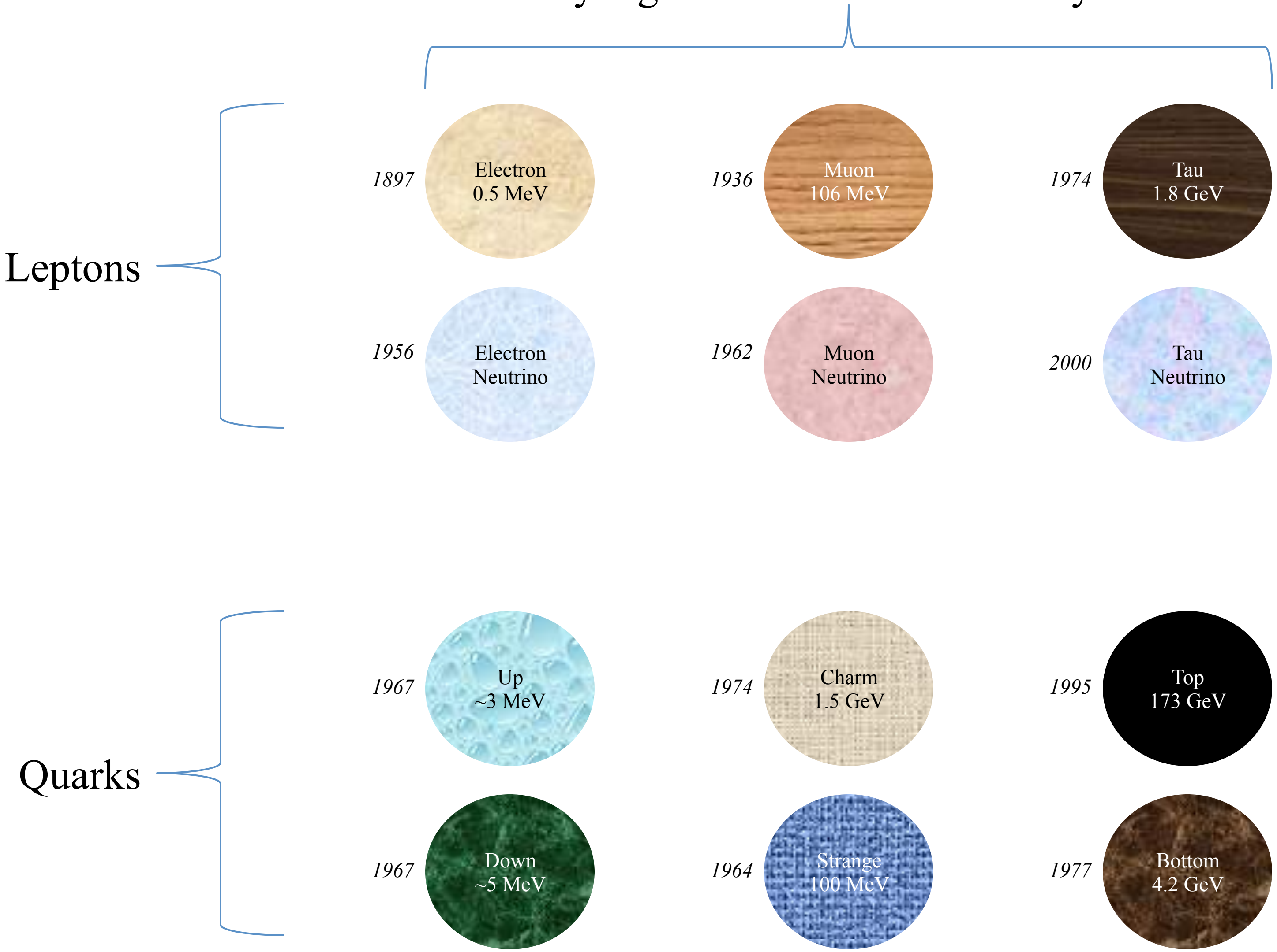


By convention there is colour,
By convention sweetness,
By convention bitterness,
But in reality there are atoms and space.

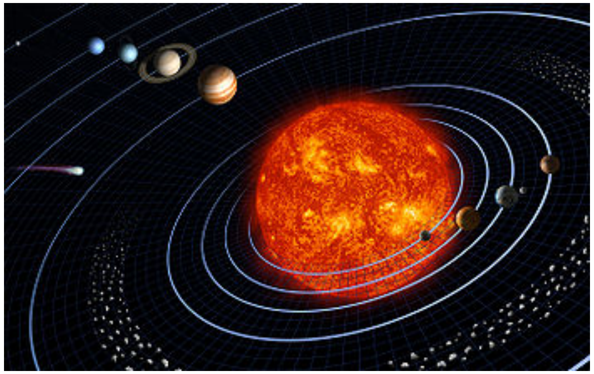
- Democritus (400 B.C.)

What is everything made of?

Why 3 generations? No one really knows!

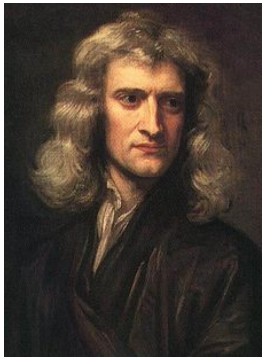


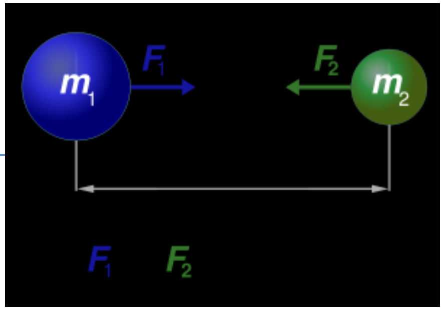
What holds everything together? – (I) Gravitation



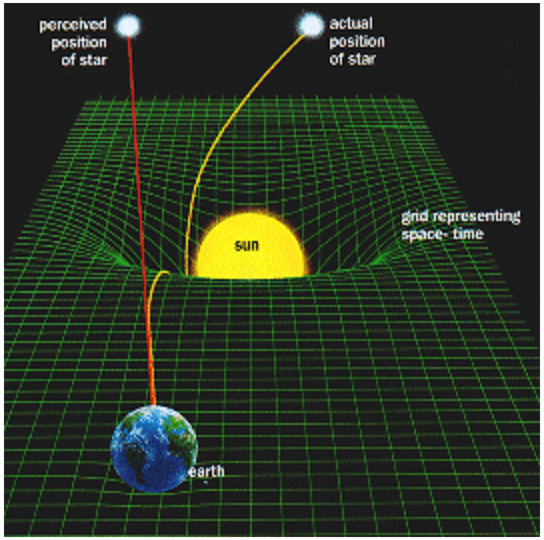
Celestial Gravitation

Terrestrial Gravitation





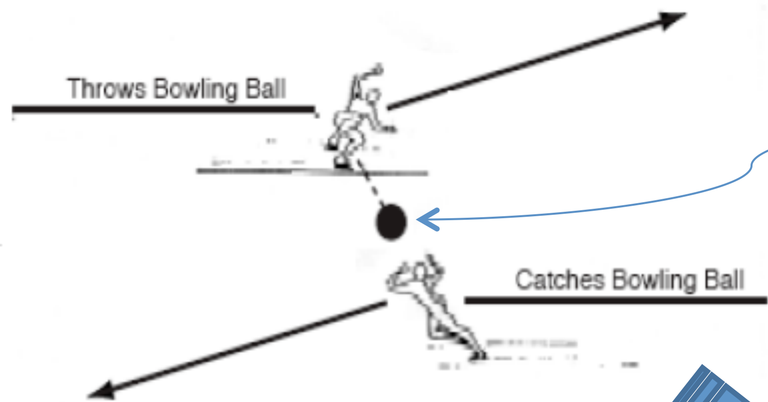
Newton's Law of **Universal Gravitation**



Einstein's **General Theory of Relativity**

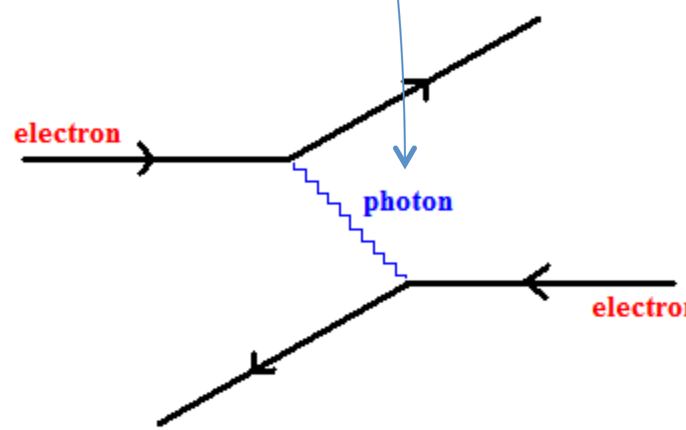
Forces as Interactions

All forces can be thought of as interactions between elementary particles.



All forces are mediated by a force-carrying particle.

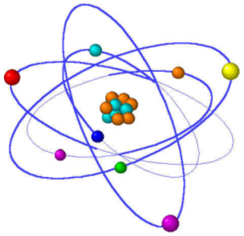
Richard Feynman



A Feynman Diagram for two electrons repelling each other

What holds everything together? – (II) Electromagnetism

Electricity



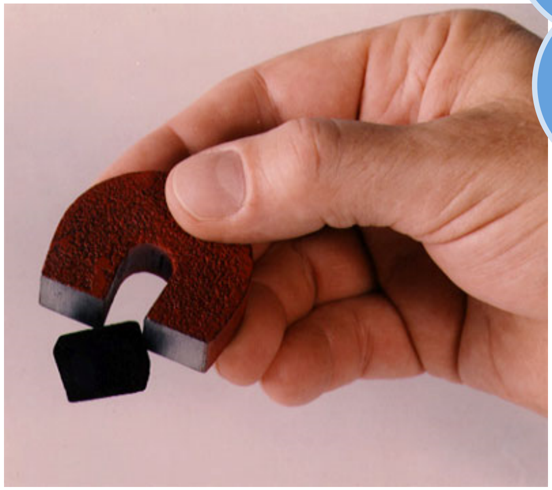
Chemistry

Light

The Electromagnetic Force

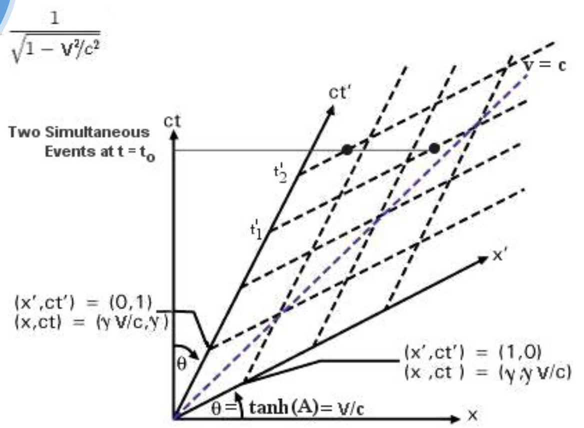
- Felt by all charged particles
- Carried by particles called *photons* in the quantum theory

Photon
0 mass

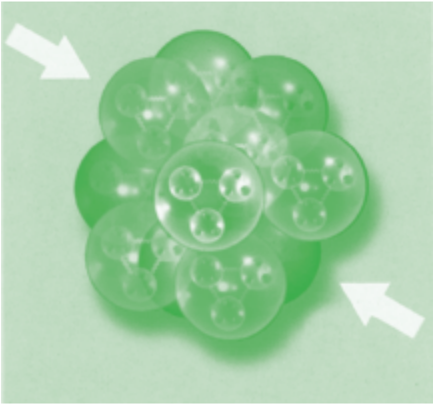


Magnetism

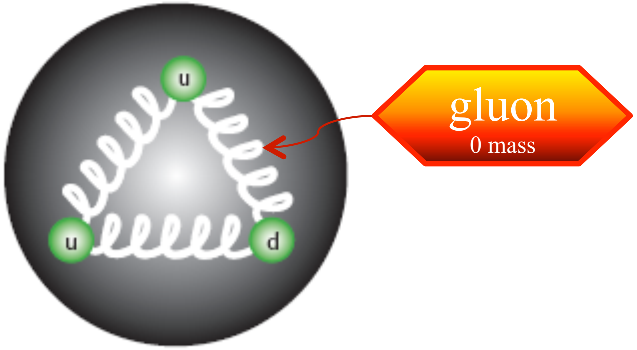
4 dimensional space-time



What holds everything together? – (III) Strong Nuclear Force



Binds protons and neutrons together to form atomic nuclei

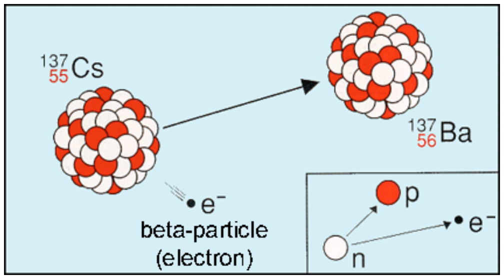


Binds quarks together to form protons and neutrons

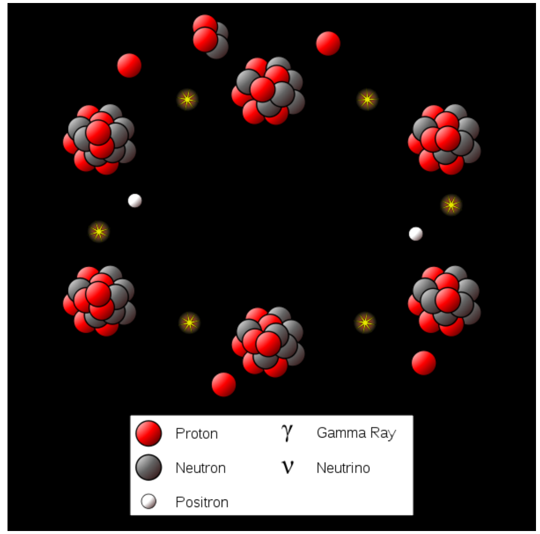
The Strong Nuclear Force

- Holds nuclei and nucleons together.
- Quarks and gluons feel this force
- Mediated by particles called *gluons*
- Very short in range

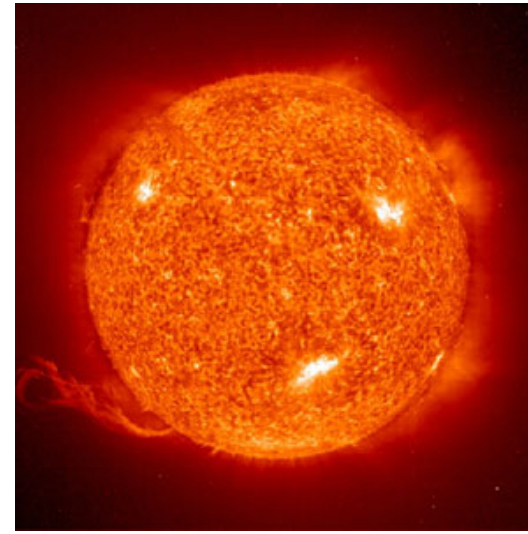
What holds everything together? – (IV) Weak Nuclear Force



Officiates nuclear (beta) decays



Give us nuclear cycles…

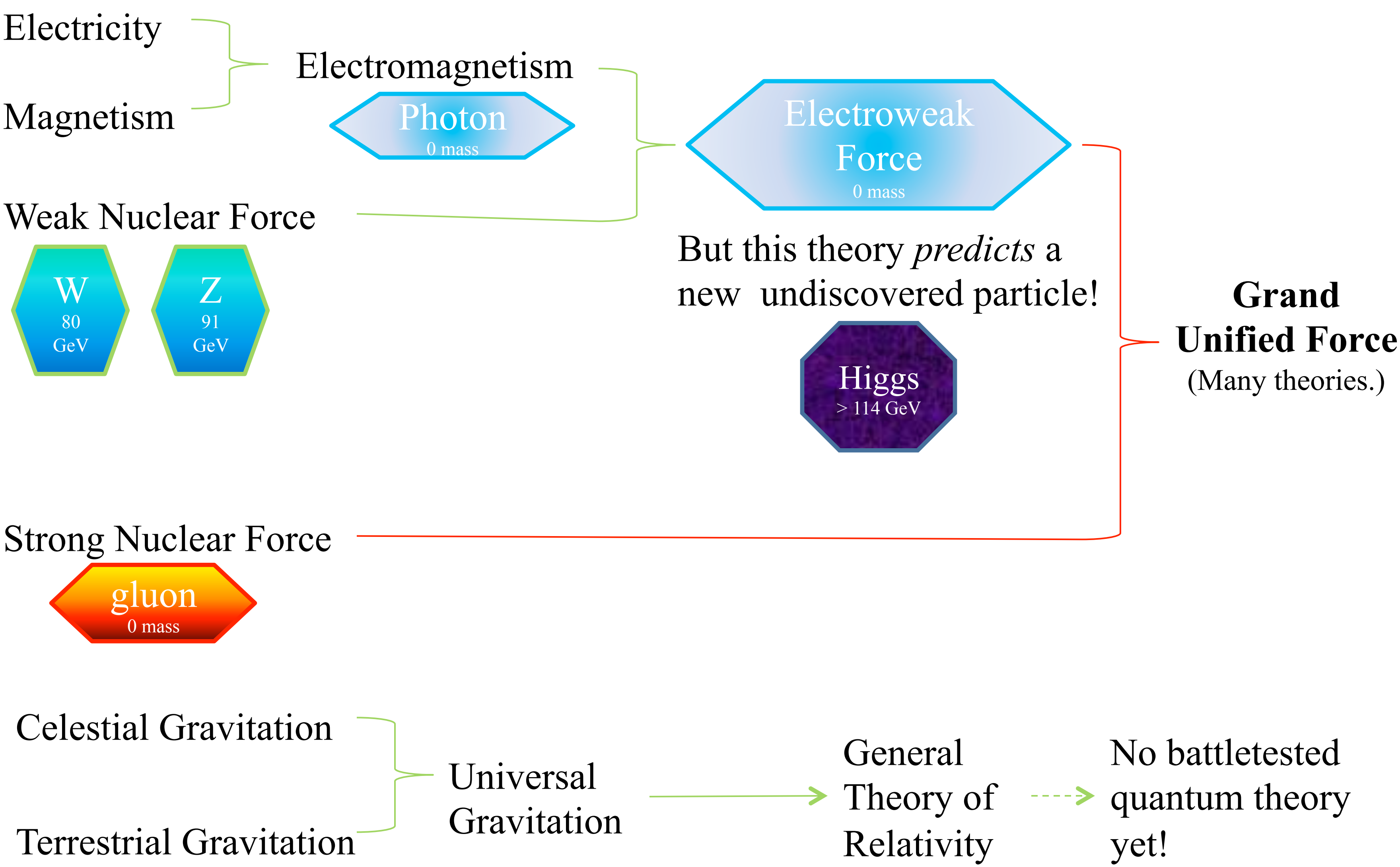


… that powers our sun and other stars.

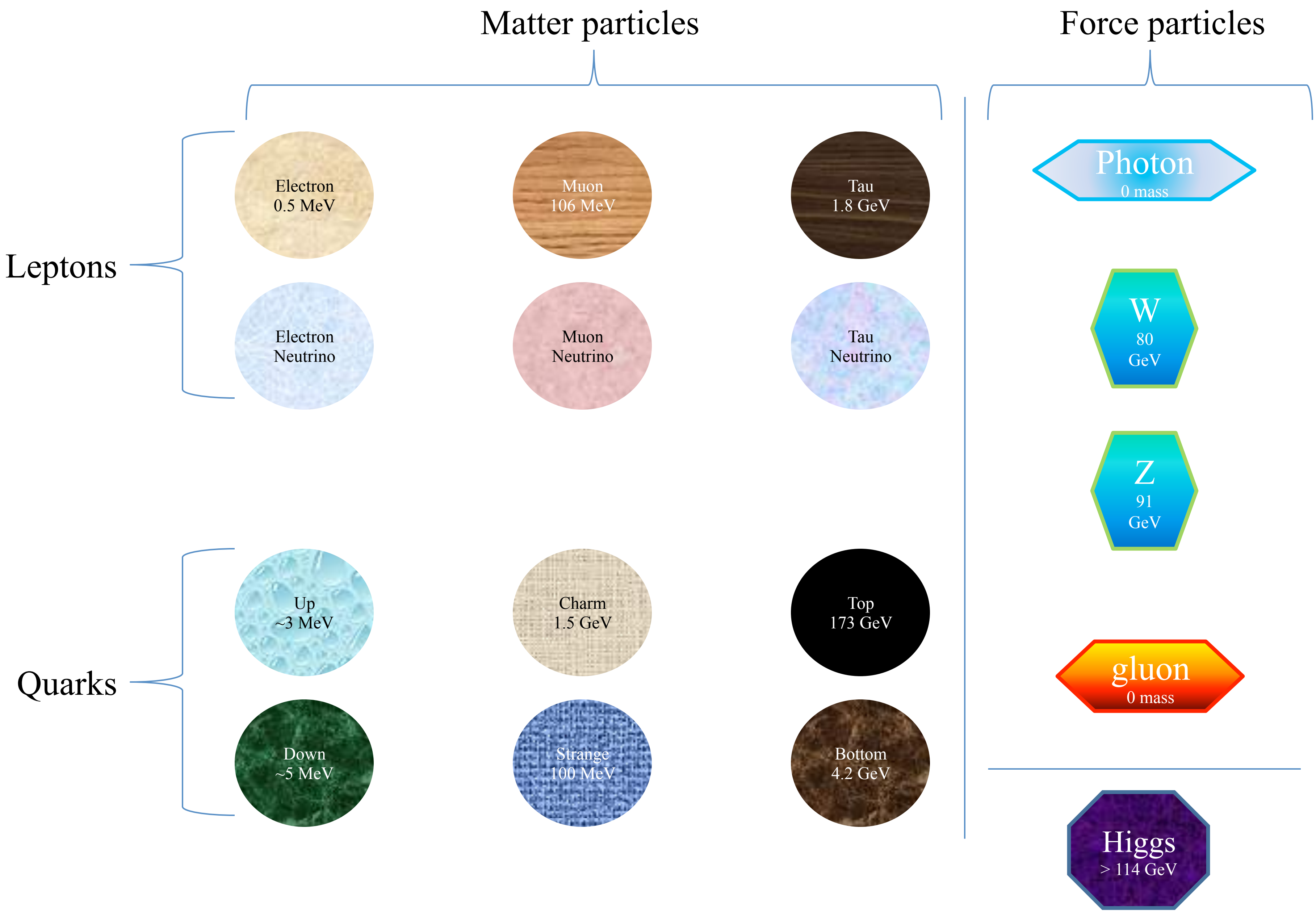
The Weak Nuclear Force

- All matter particles feel this force
- Mediated by particles called *W and Z bosons*
- Short ranged

The Quest for Unification



The Standard Model of Particle Physics



Outstanding Mysteries – The Mystery of Mass

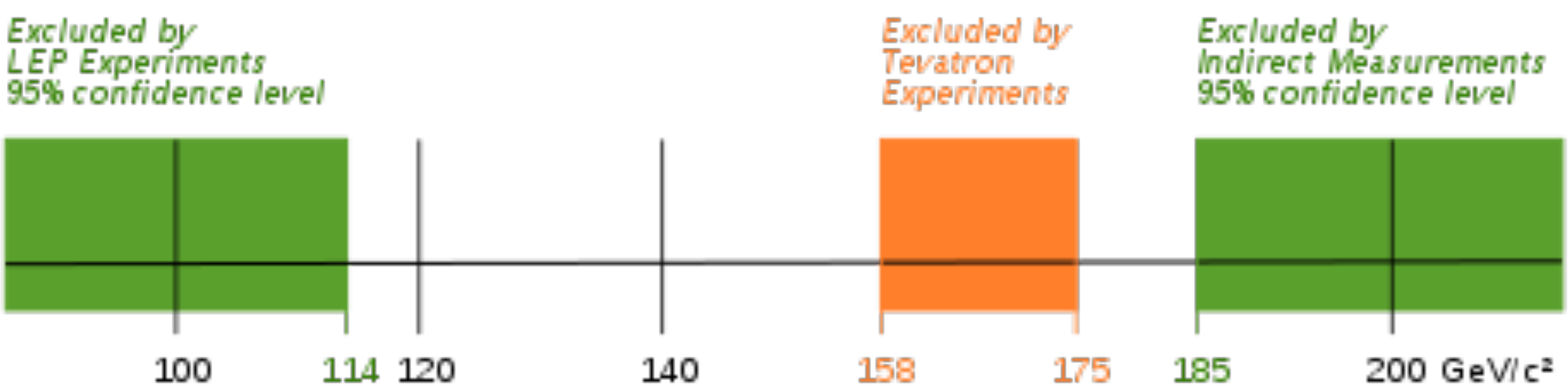
The *Higgs Boson*

•Required by the Glashow-Salam-Wienberg theory of Electroweak Unification.

- •Places the γ, *W* and *Z* on the same footing as symmetrical cousins.
- •But introduces the *Higgs boson* to break this symmetry and lend the *W* & *Z* mass.

• Accurately predicts the ratio of masses of the *W* and *Z* bosons in terms of the strengths of the electromagnetic and weak forces.

• Provides the simplest mechanism for a matter particle of the Standard Model to have mass within the framework of quantum fields.



Outstanding Mysteries – Unification of the Forces

Higgs
> 114 GeV

Electroweak Unification

•We need to discover the Higgs boson to wrap up the story of Electroweak Unification.

Grand Unification and Supersymmetry

Electroweak Force
0 mass

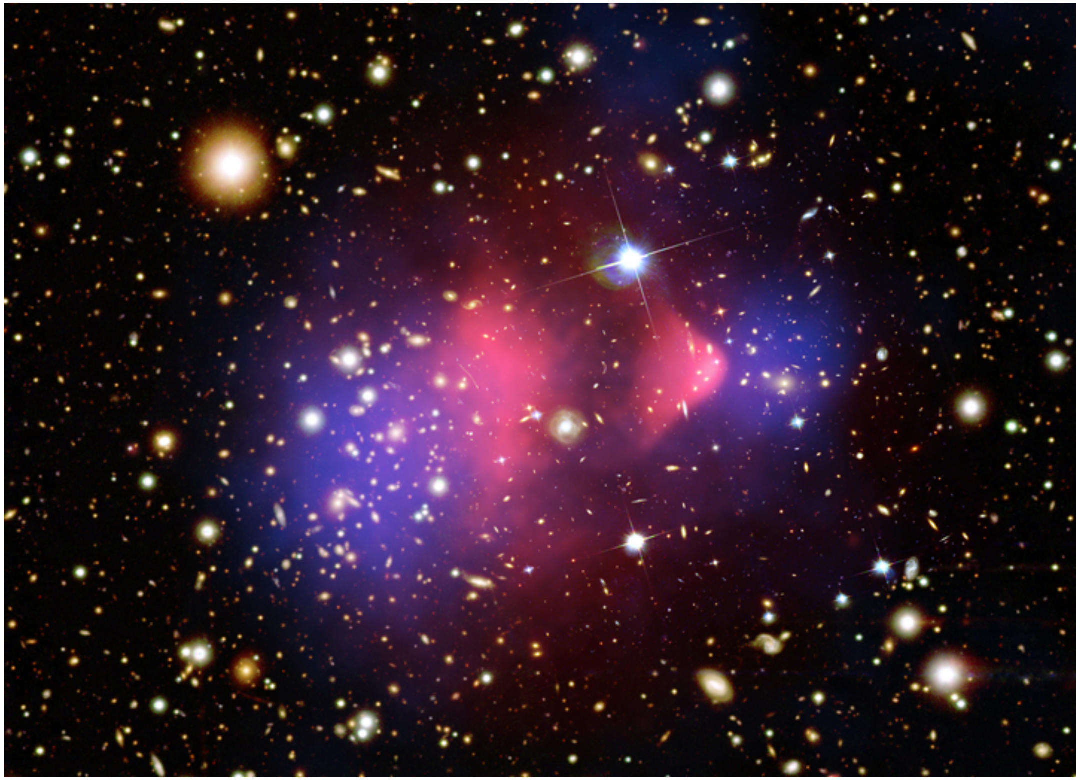
•Every matter particle follows Fermi-Dirac statistics. Every force carrier particle follows Bose-Einstein statistics. There is theoretical reason to believe that every matter particle has a "supersymmetric" twin with identical charge properties but following Bose-Einstein statistics. And every force carrier particle has a "supersymmetric" twin with identical force carrying properties but following Fermi-Dirac statistics.

•*Supersymmetry* offers a compelling way to unify the Electroweak and Strong forces.

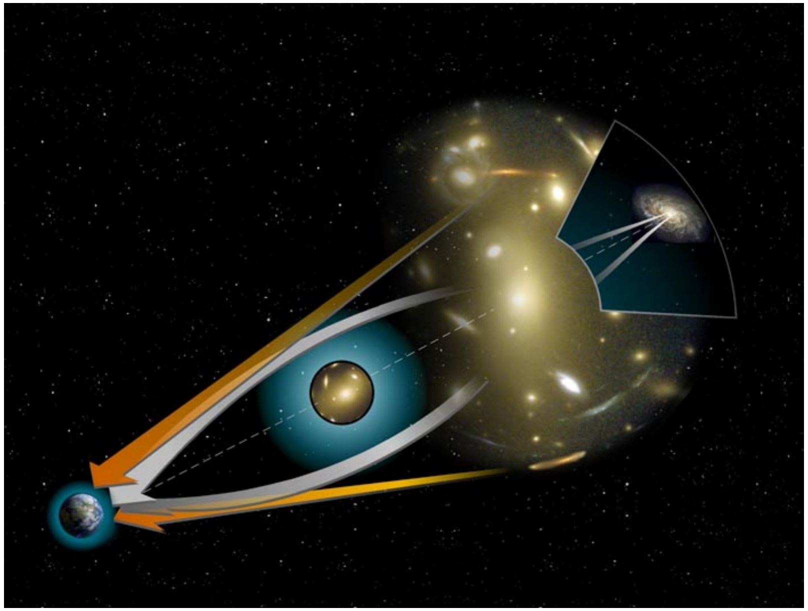
•*Supersymmetry* can also offer explanations of the *Higgs* mass.

gluon
0 mass

Outstanding Mysteries – Dark Matter



The Bullet Cluster (1E 0657-56). Two galaxies colliding. Red shows concentration of visible matter. Blue shows dark matter inferred by gravitational lensing.



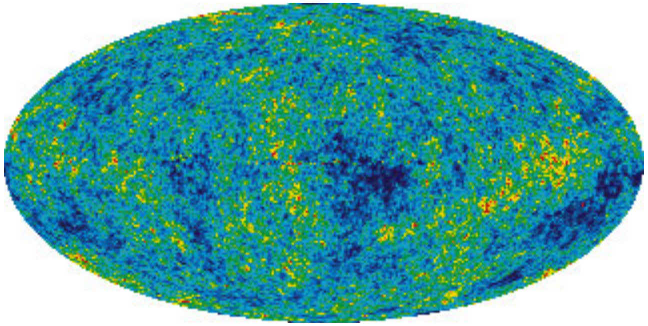
Gravitational lensing

<u>What is dark matter composed of?</u>

•*Supersymmetric* particles perhaps?
•The lightest supersymmetric particle predicted by theory, the *neutralino*, has all the right properties!

Outstanding Mysteries – The Matter Antimatter Asymmetry

Where is all the antimatter in the universe?



The **cosmic microwave background** shows no patch of antimatter

If the universe began from pure energy, we should have equal amounts of matter and antimatter.

But equal amounts of matter and antimatter would have annihilated into radiation if the rate of annihilation was greater than the rate of expansion of the universe.

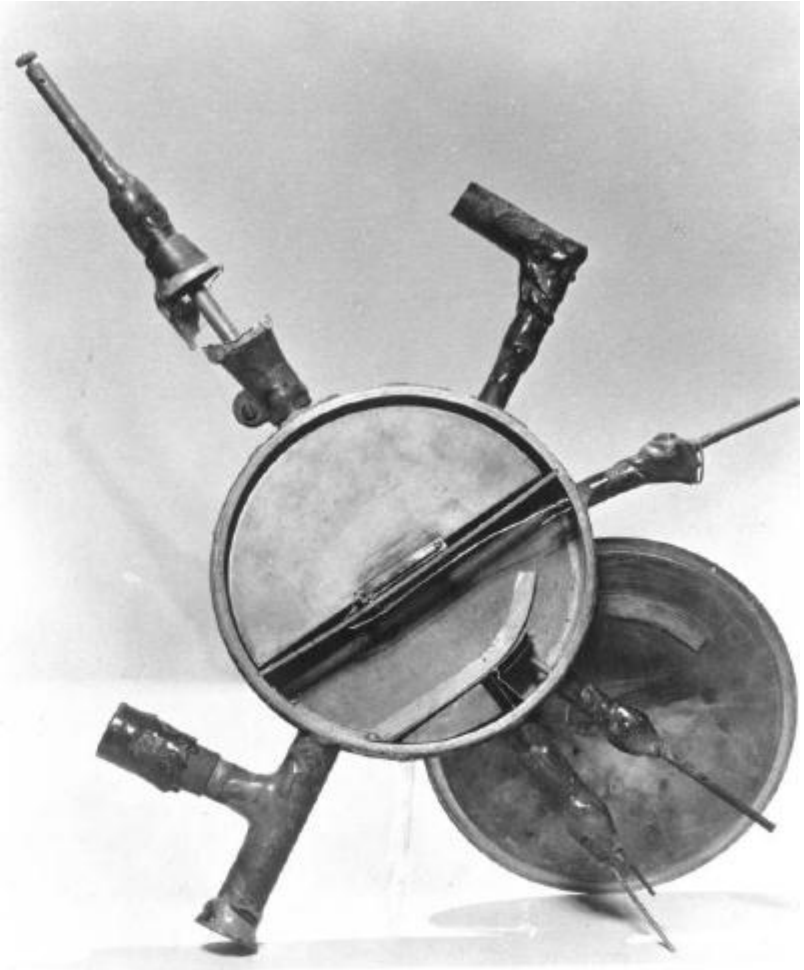
We are still here and no naturally occurring antimatter is in sight! We've looked for zones of annihilation radiation and found none.

Sakharov Conditions. Necessary for matter-antimatter asymmetry

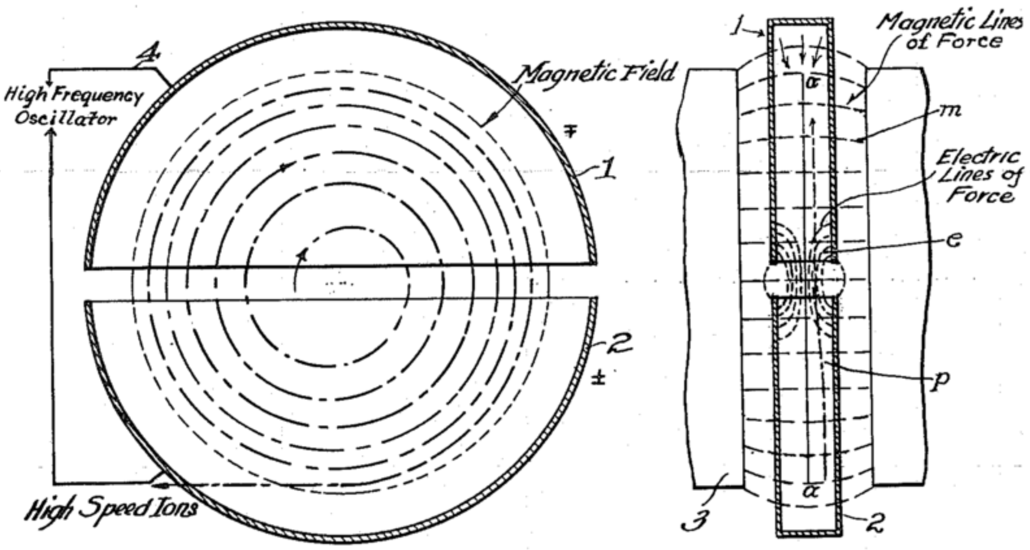
1. Baryon number violation
2. *Charge* symmetry and *Charge-Parity* symmetry violation
3. Universe expanding out of equilibrium for reaction generating matter asymmetry

Tools of the Trade

The Particle Accelerator



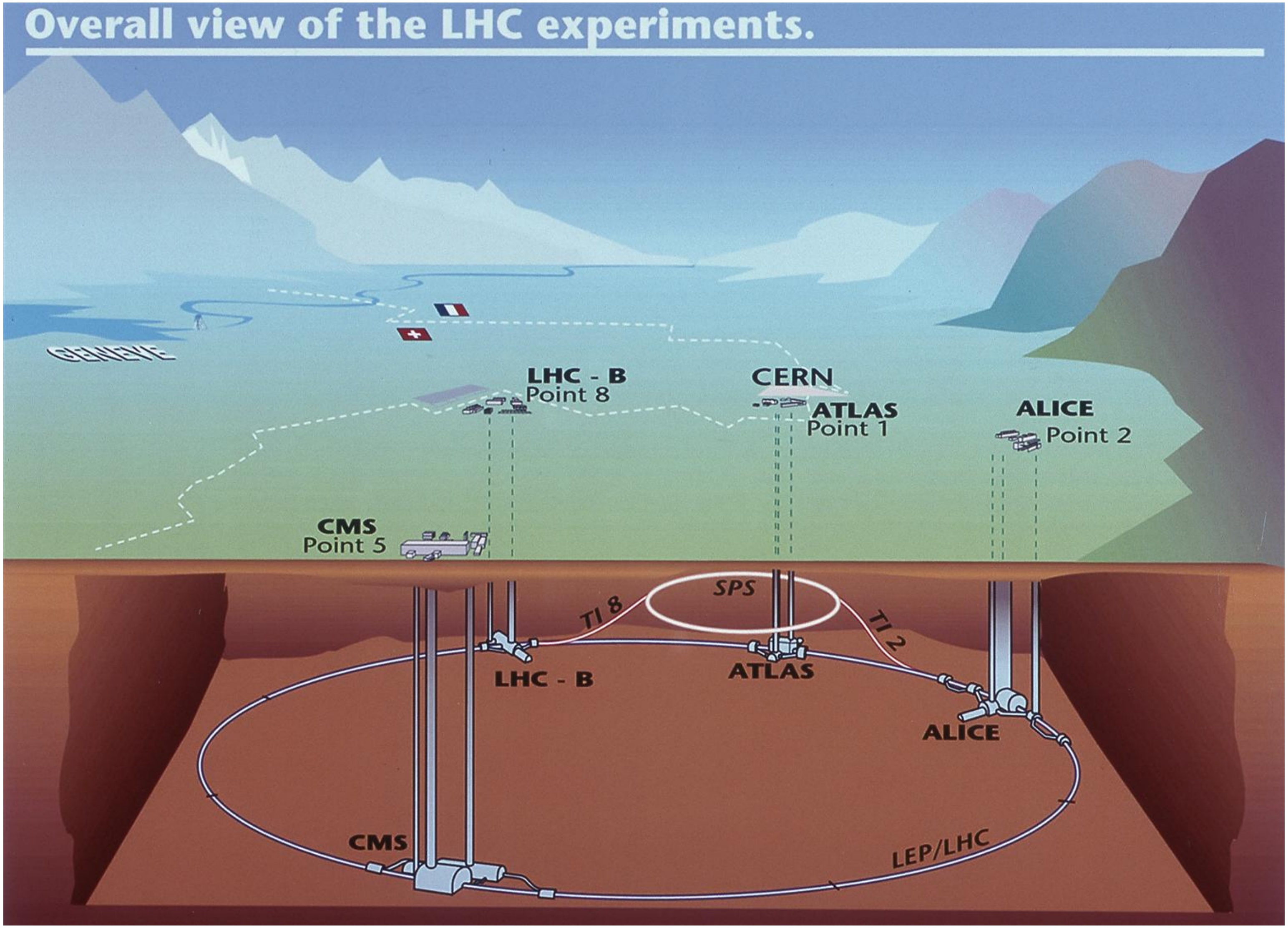
The first particle accelerator (cyclotron) developed by Ernest O. Lawrence in 1929



The patent to the first particle accelerator (cyclotron) developed by Ernest O. Lawrence in 1929

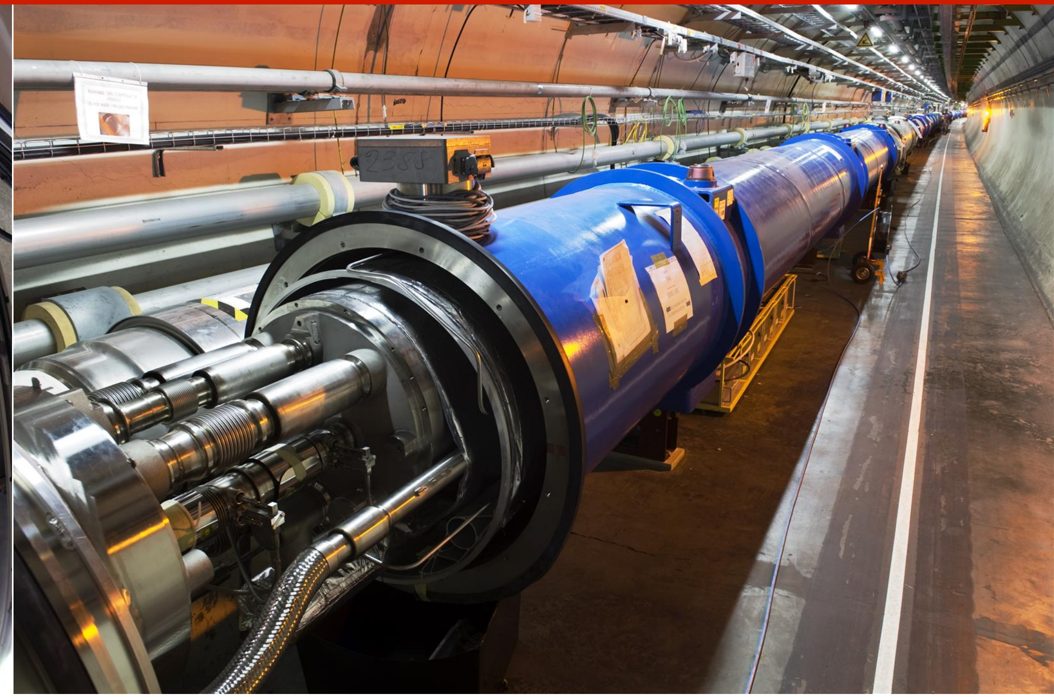
- Ionize some atoms so they become charged
- Speed them up using electrical fields
- Curve them in a manageable track using magnetic fields
- Once at sufficient speed, smash them into something!
- Have particle detectors handy to "see" what comes out. New particles perhaps?

The Particle Accelerator



- 100 m below the surface
- 27 km in circumference

The Particle Accelerator

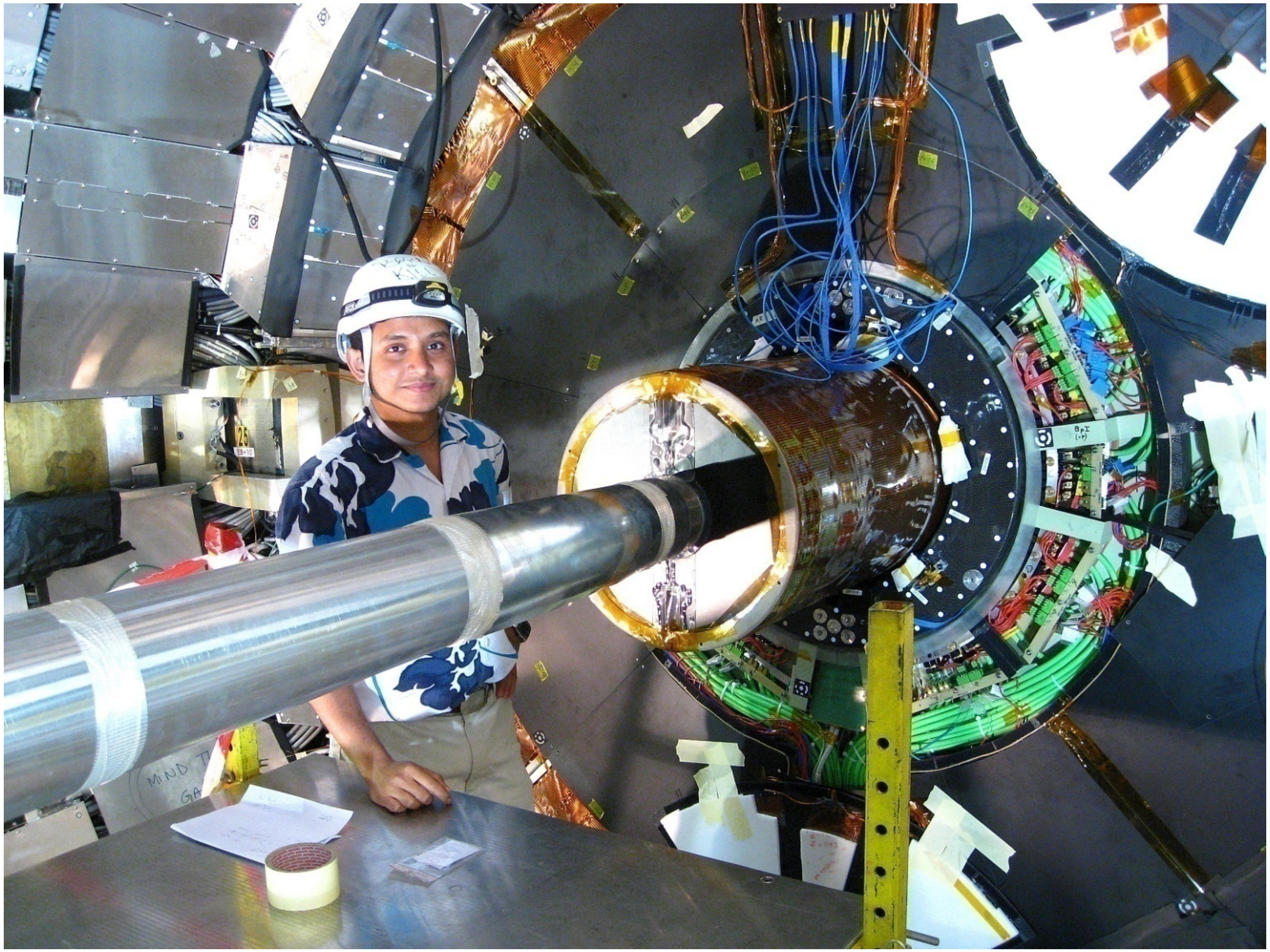


•Giant dipole electromagnets (time-varying) are used to accelerate the protons. Each is 15m long and weighs 35 tons.

•20 km of superconducting dipole magnets using 96 tons of superfluid helium at 1.9 K

•8.3 T magnetic field required to keep protons in circular track. Draws a current of 11,700 A. Average family house draws less than 70 A.

The Particle Accelerator

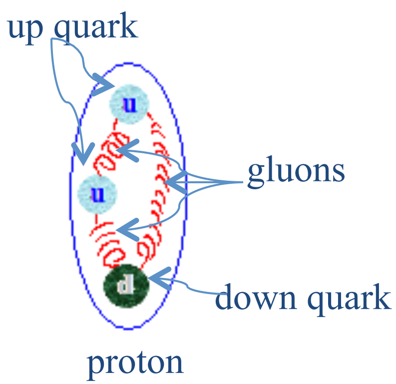


Near the collision point of the CMS experiment

- The pipe carrying the beam of protons is evacuated to 10^{-13} atmospheres of pressure to avoid protons colliding into stray atoms.

- The counter rotating beams of protons, each carrying about the energy of a 400 ton train traveling at 150 km/h, are made to crash at the center of each experiment.

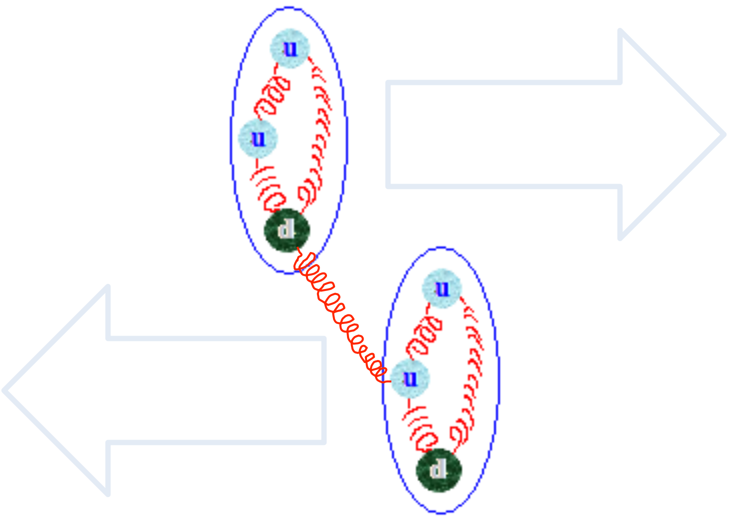
Collision Point



Travelling at 99.999999% the speed of light, carrying 7000 GeV of energy each.

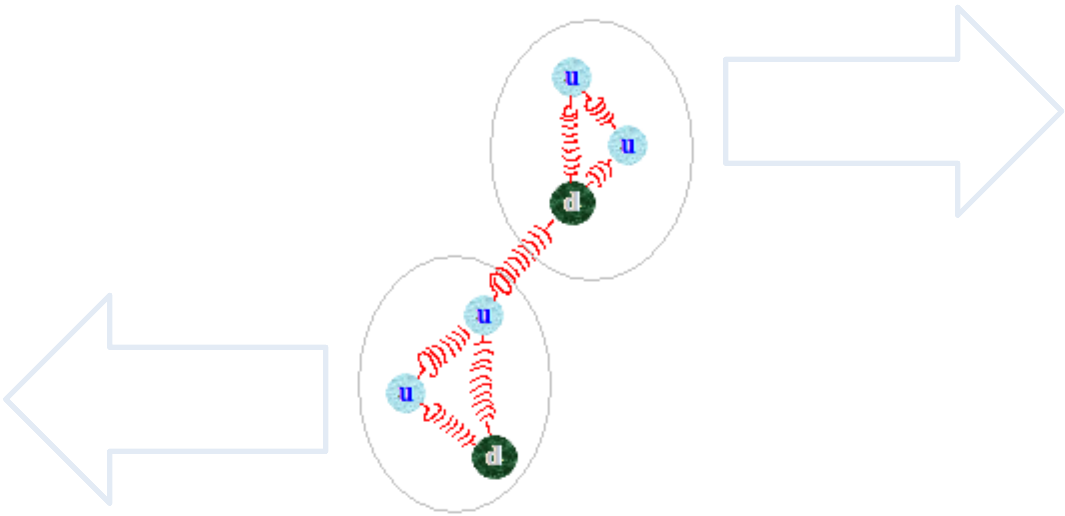
The energy allows them to overcome their mutual electromagnetic repulsion and **allows their quarks and gluons to interact** via the strong nuclear force.

The Crash – Approach



Quarks of different protons begin to feel each other through gluons because they are so close!

The Crash – Interaction



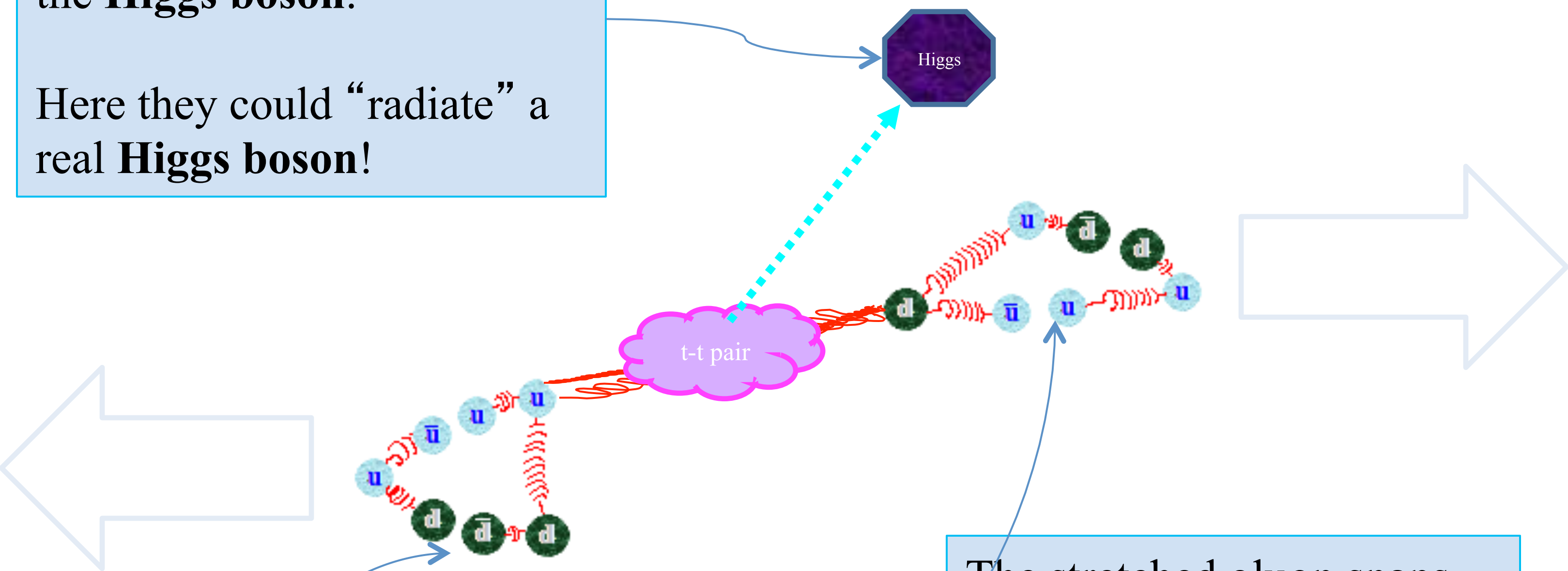
The newly formed gluon is under high tension now!

And so may be the other gluons since the whole protons received a tremendous shock.

The Crash – Production of New Particles!

Top quarks are quite heavy and hence couple strongly to the **Higgs boson**.

Here they could "radiate" a real **Higgs boson**!

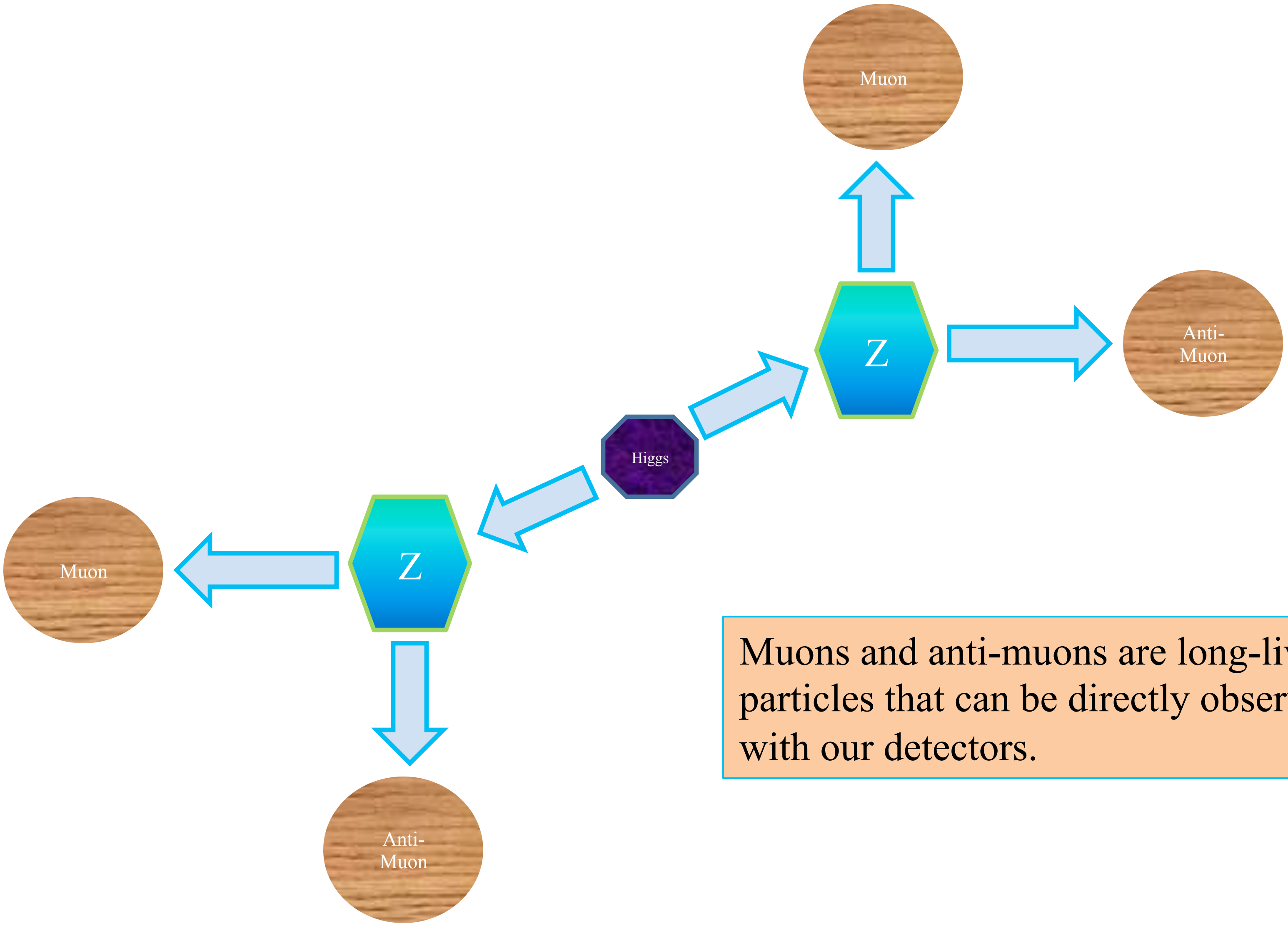


The stretched gluon snaps into a **top & antitop** quark pair of virtual particles!

Gluons snap forming **quark – antiquark pairs**!

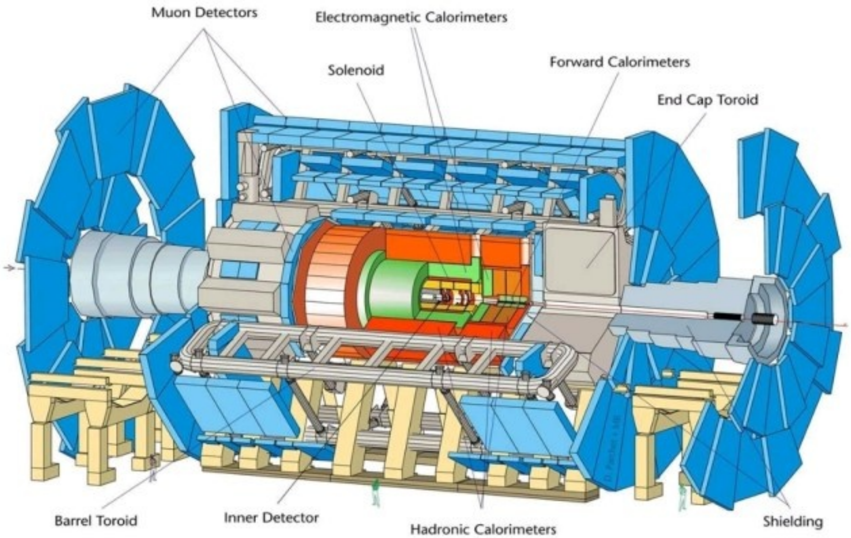
Protons fragment into sprays of newly formed hadronic debris. Don't interest us usually.

The Higgs Boson Decays into Muons

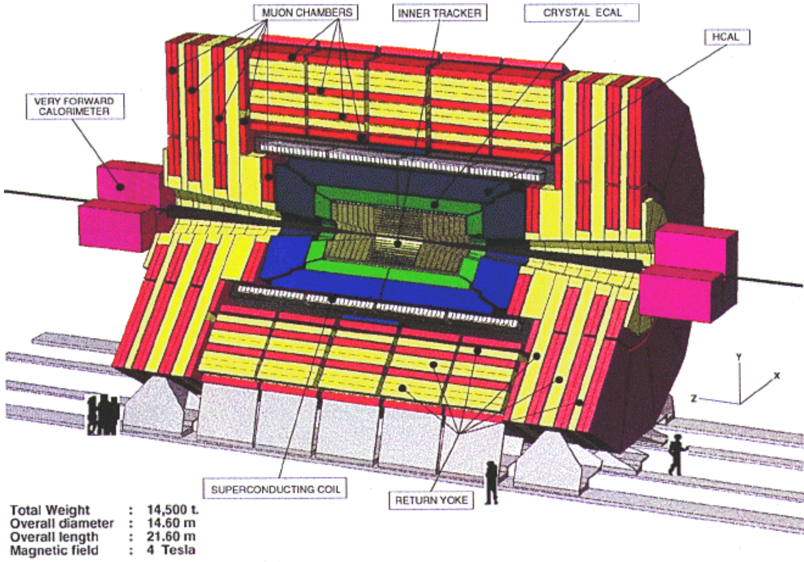


Muons and anti-muons are long-lived particles that can be directly observed with our detectors.

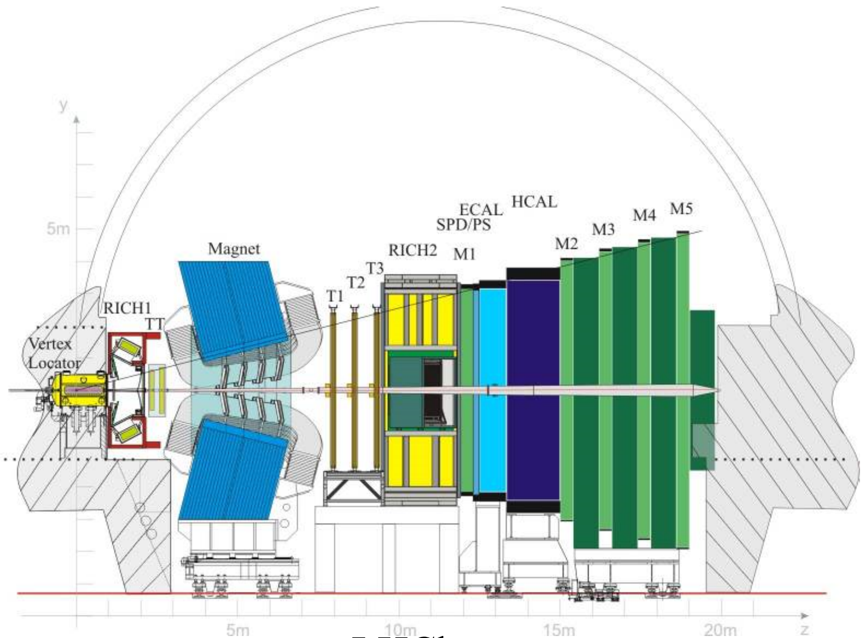
ATLAS, CMS, ALICE and LHCb



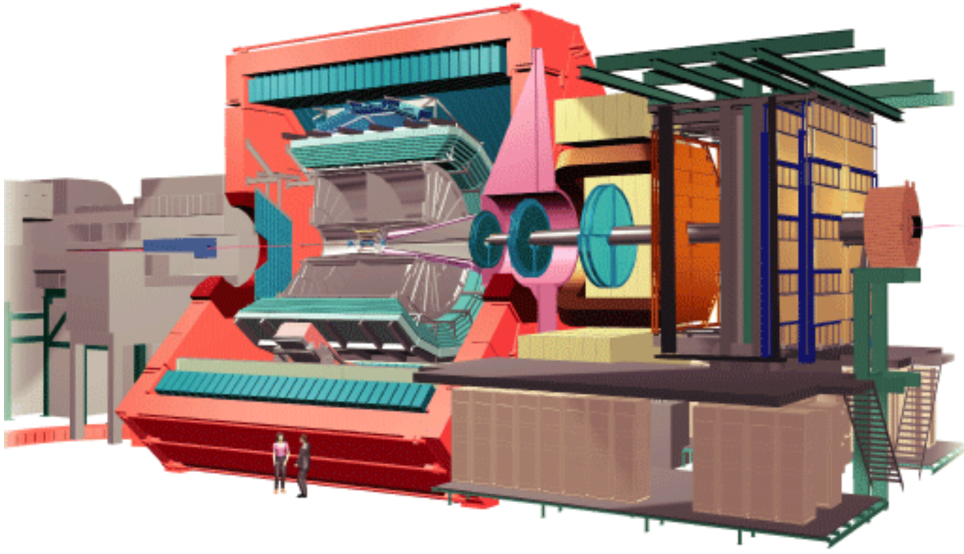
ATLAS – A Toroidal LHC Apparatus



CMS – Compact Muon Solenoid

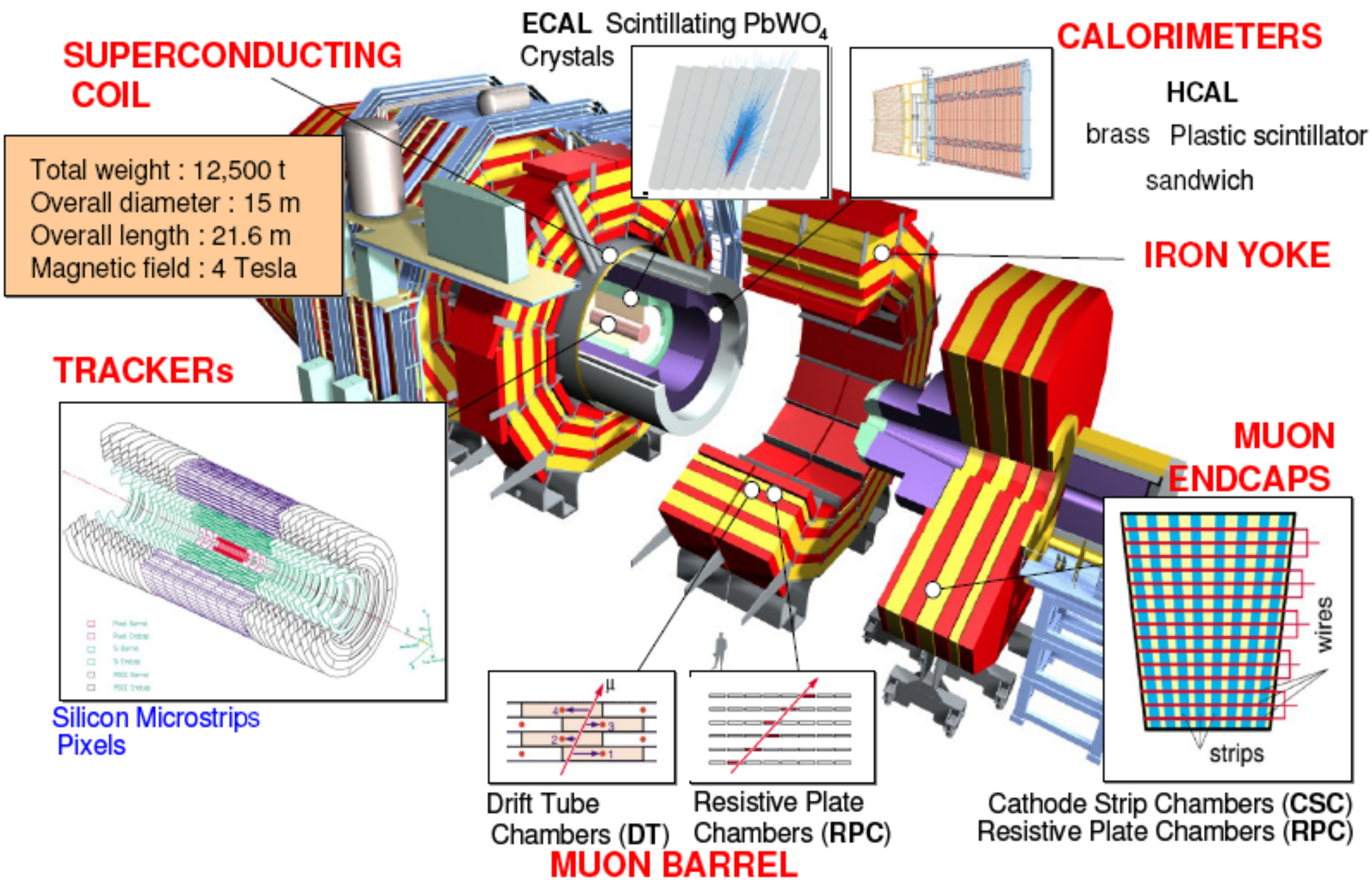


LHCb



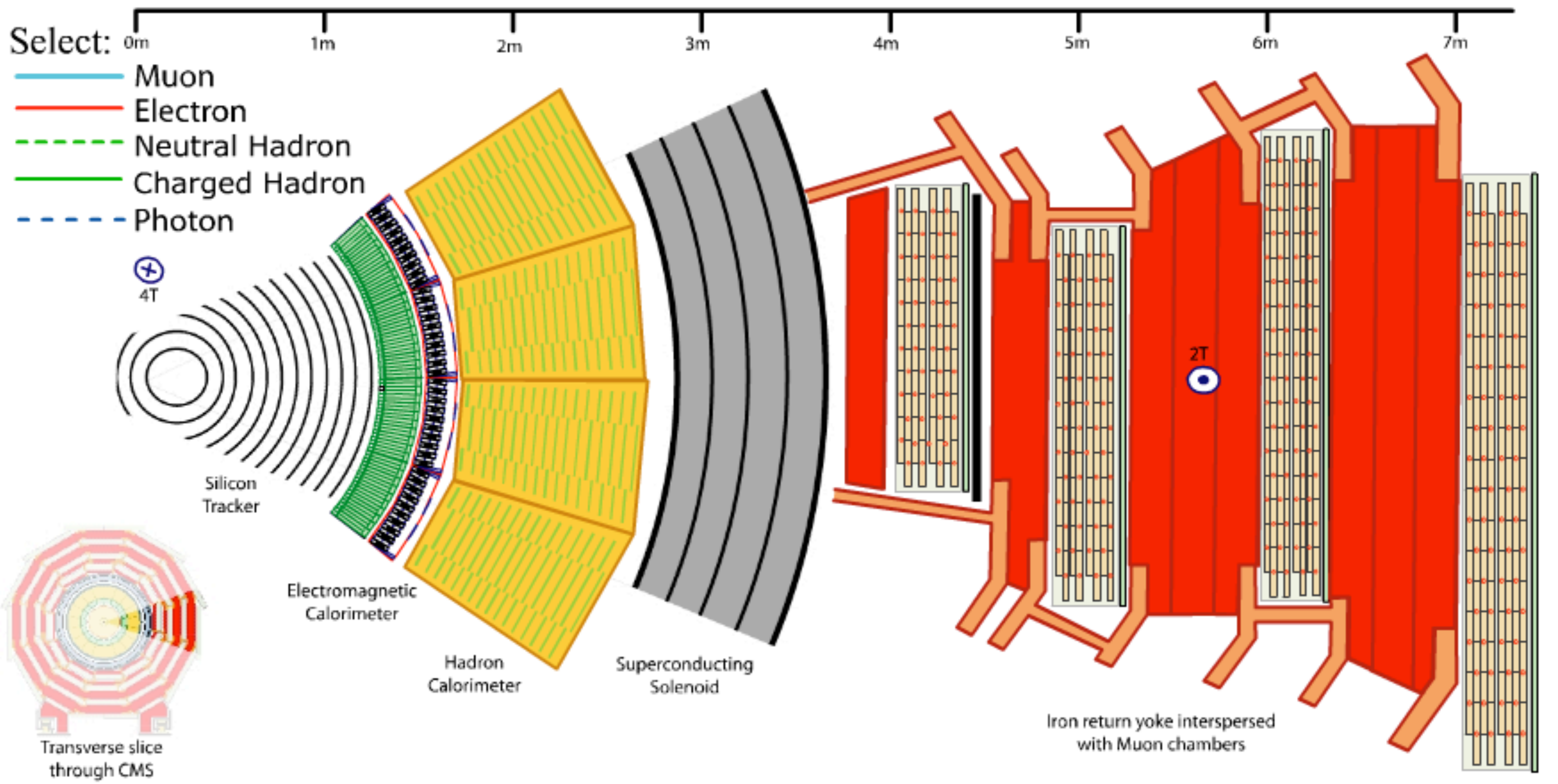
ALICE – A Large Ion Collider Experiment

CMS


SUPERCONDUCTING COIL
ECAL Scintillating $PbWO_4$ Crystals
CALORIMETERS
HCAL
brass Plastic scintillator sandwich
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
IRON YOKE
TRACKERs
MUON ENDCAPS
wires
strips
Silicon Microstrips
Pixels
Drift Tube Chambers (**DT**)
Resistive Plate Chambers (**RPC**)
Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)
MUON BARREL

CMS

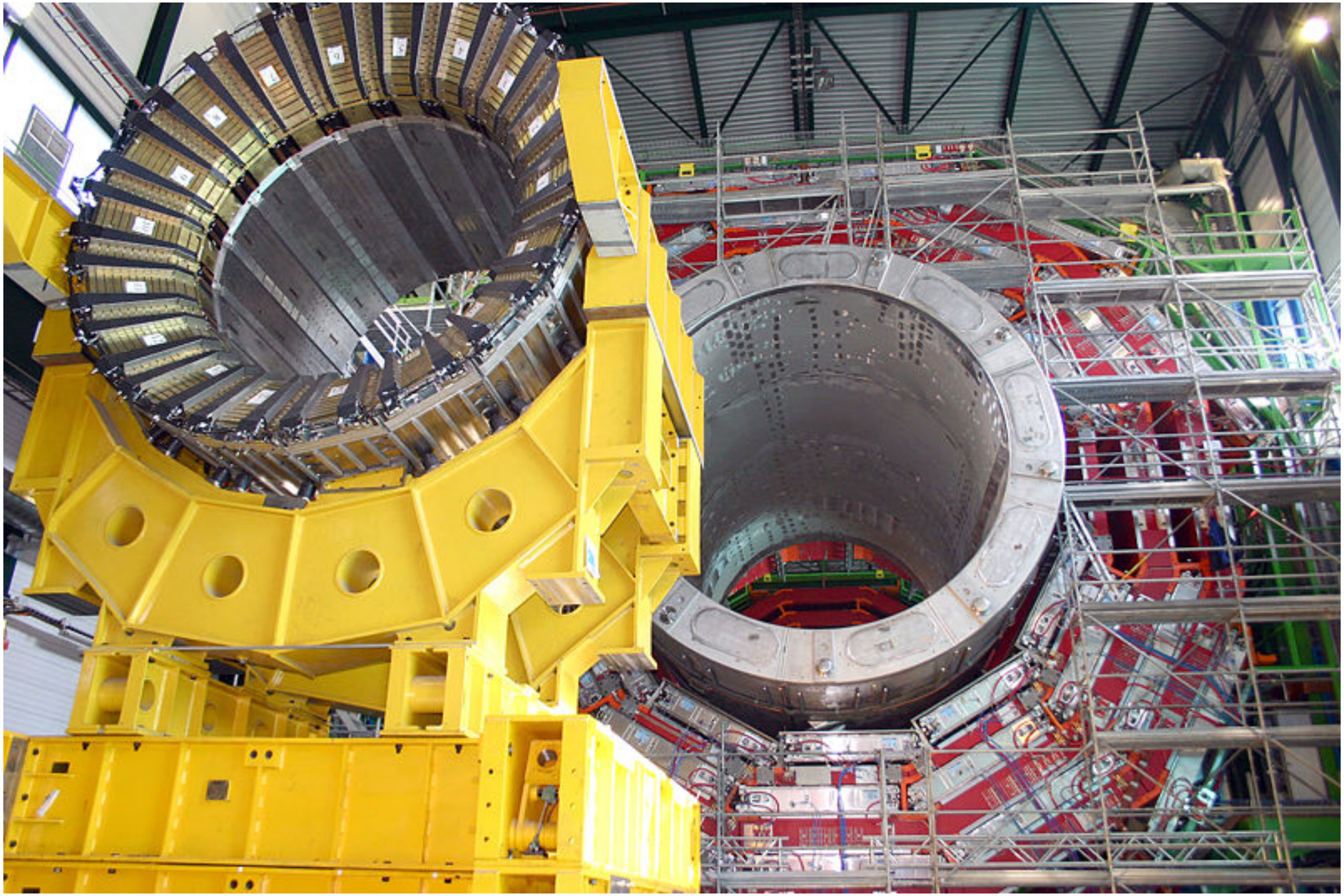
Five types of particles can be identified by the Compact Muon Solenoid detector. The existence of other particles and particles that decayed must be inferred.



CMS – Muon Chambers

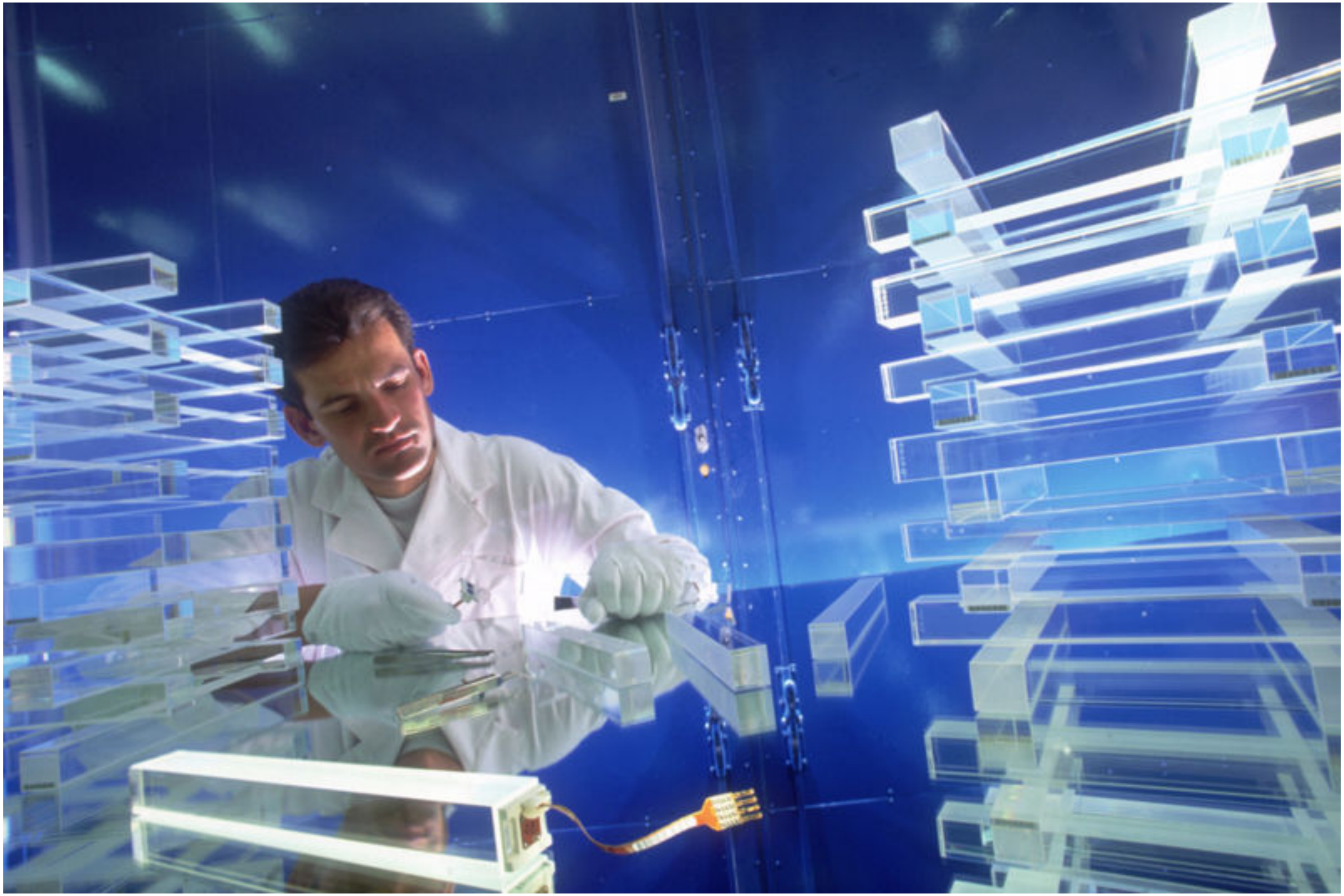
Drift tubes to detect muons

CMS – Hadronic Calorimeter



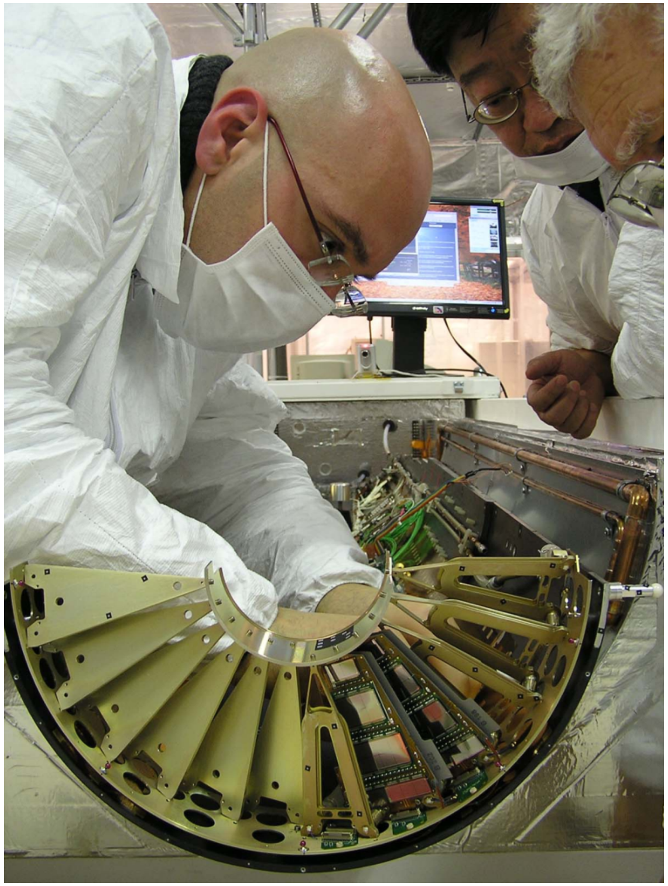
CMS HCAL being inserted into the solenoid

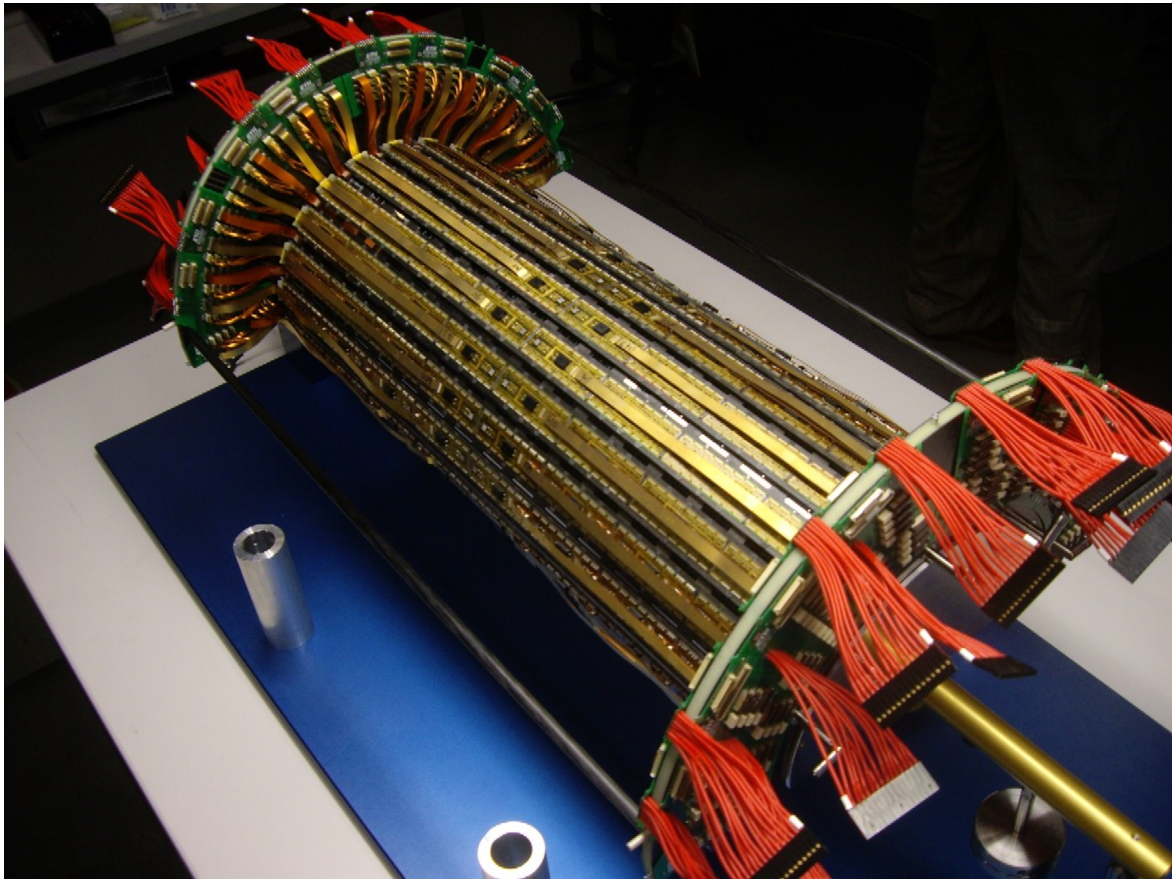
CMS – Electromagnetic Calorimeter



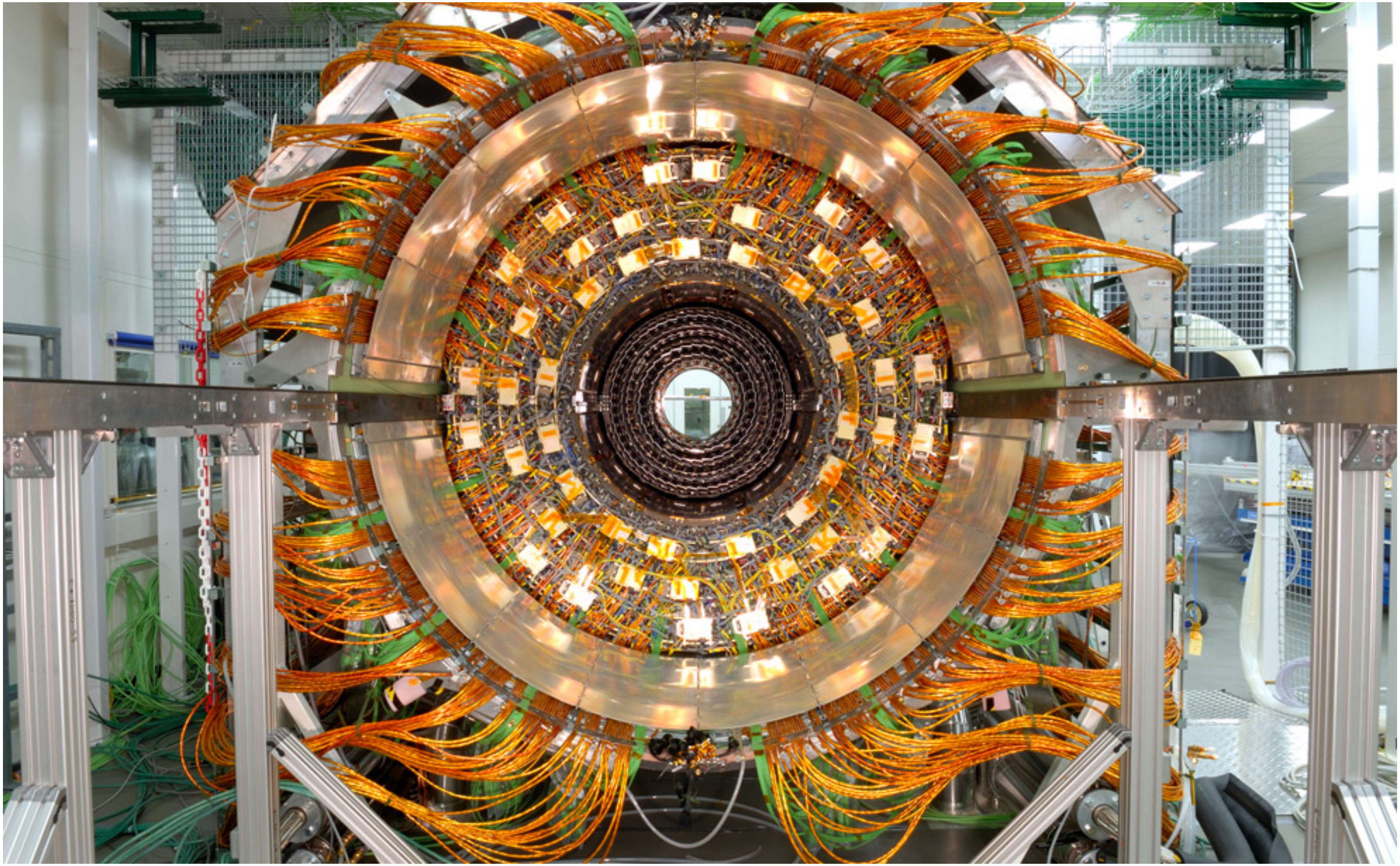
Quality testing the ECAL crystals

CMS – Pixels



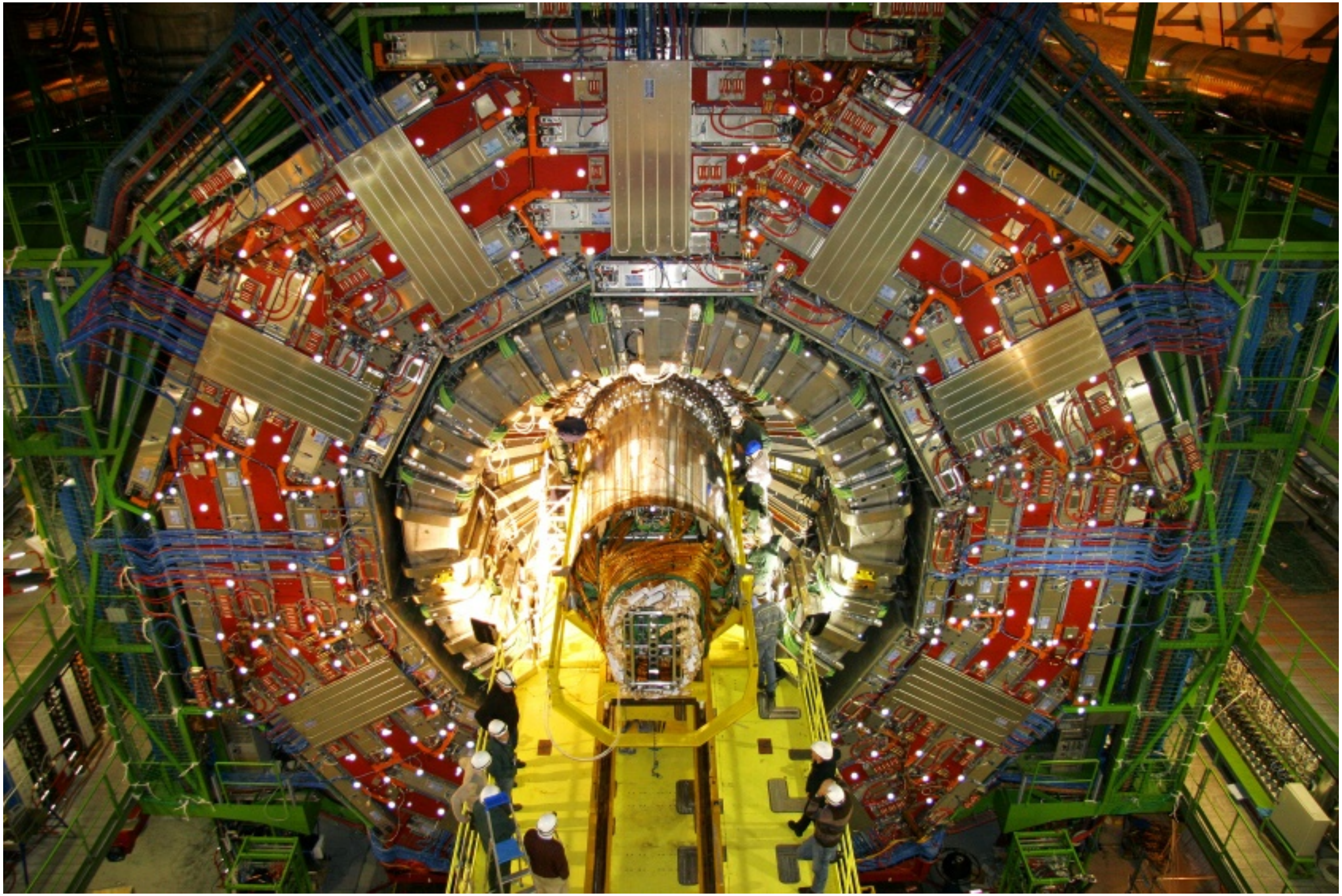


CMS – Tracker



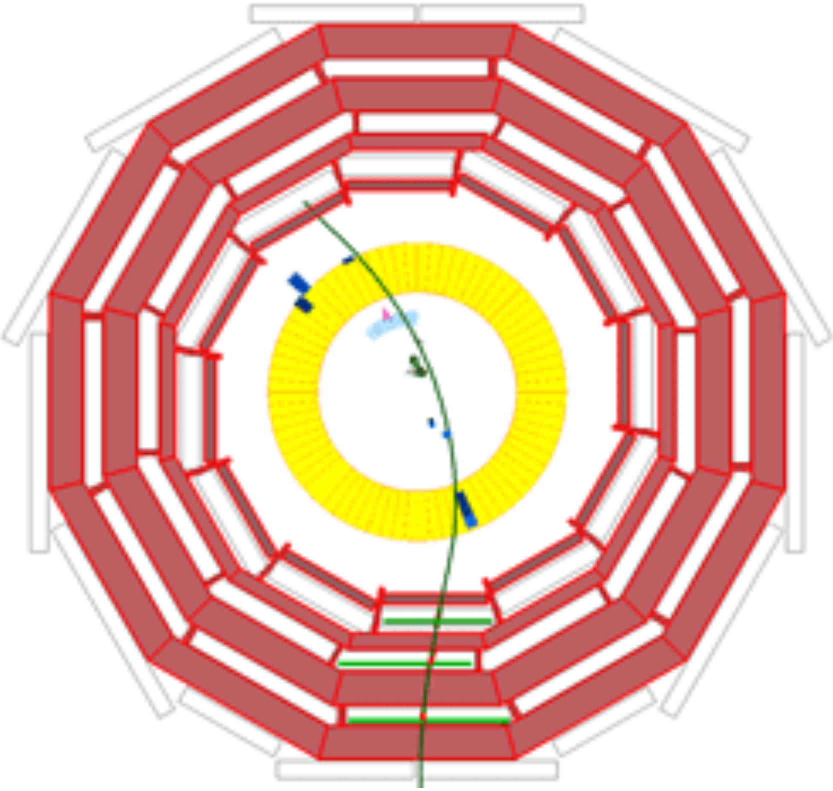
Wired up and ready to go!

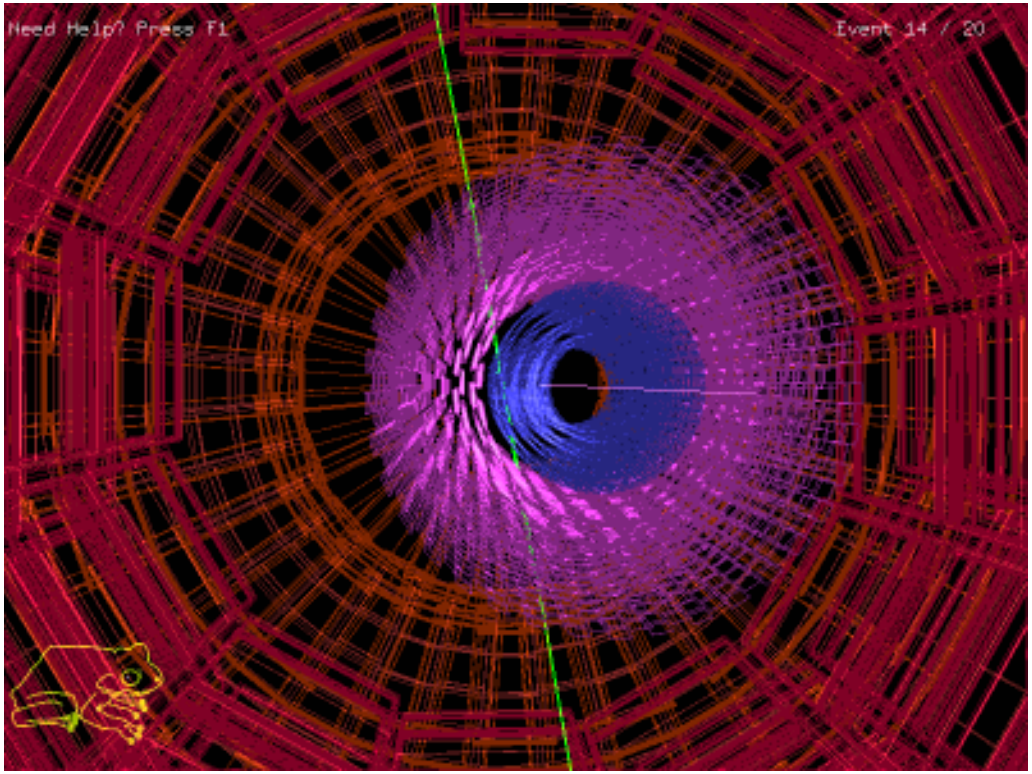
CMS



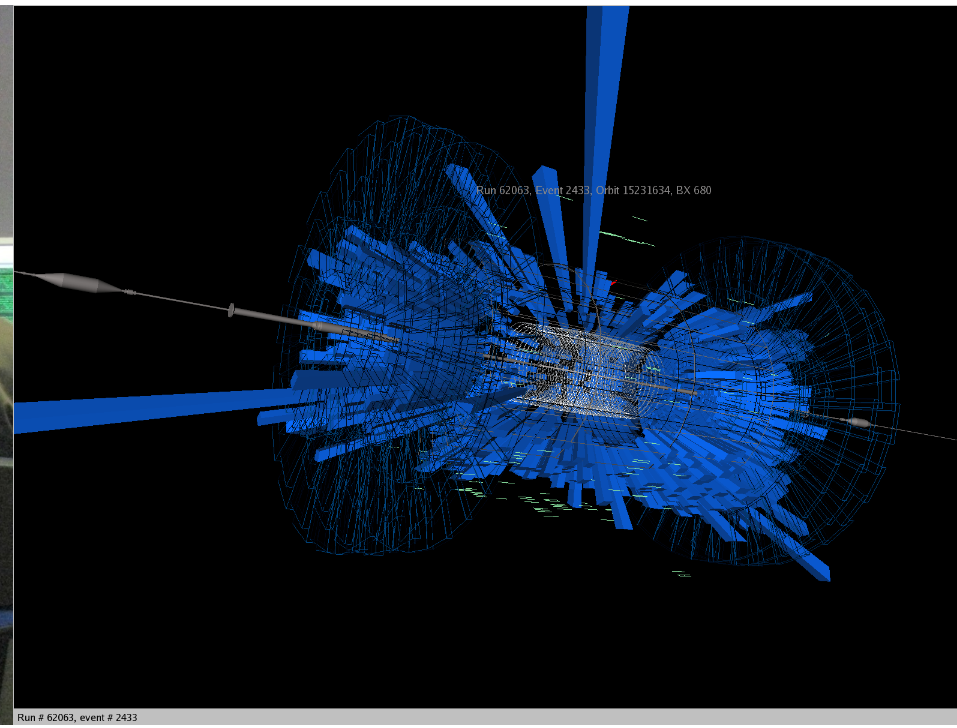
Inserting the Silicon Tracker of the CMS Detector

Cosmic Muons in CMS



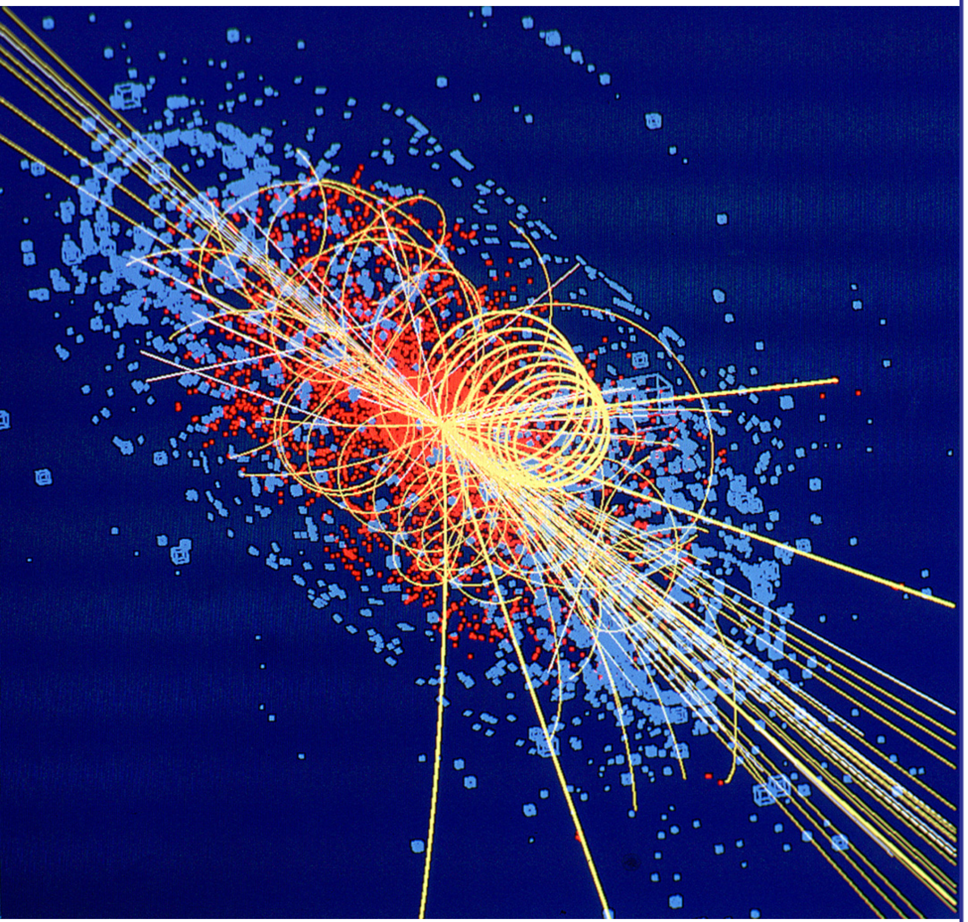


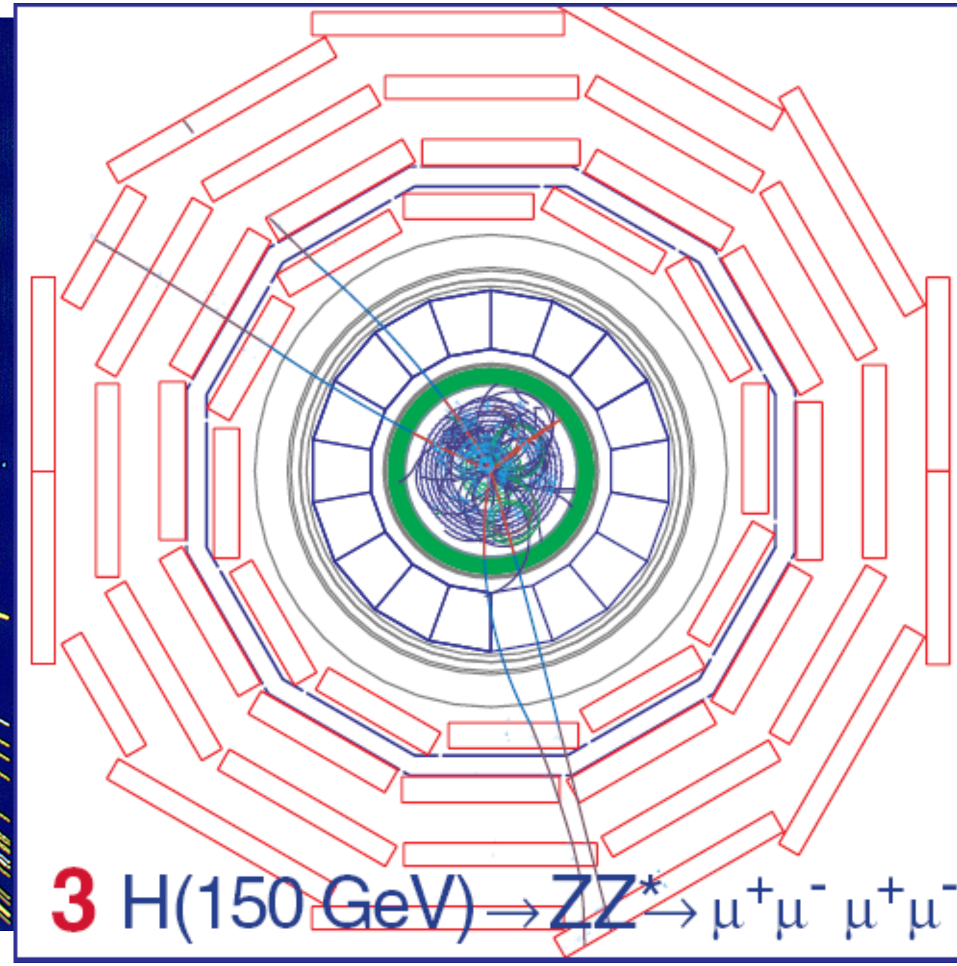
Beam through CMS (10^{th} September 2008)



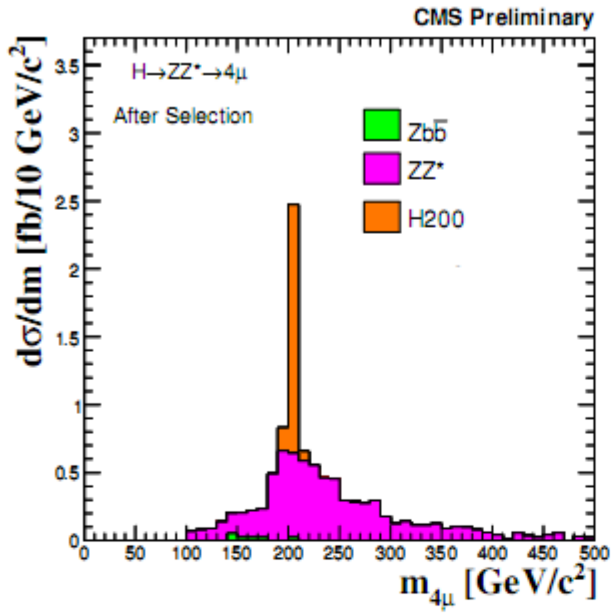
First beam data from CMS on 10^{th} September 2008 from the control center

A Higgs in CMS (simulation)





A Higgs in CMS (simulation)



Recall $E^2 = p^2c^2 + m^2c^4$

This holds true for the energy and momentum of the Higgs boson.

The energy of the Higgs boson is the scalar sum of the energies of the 4 muons.

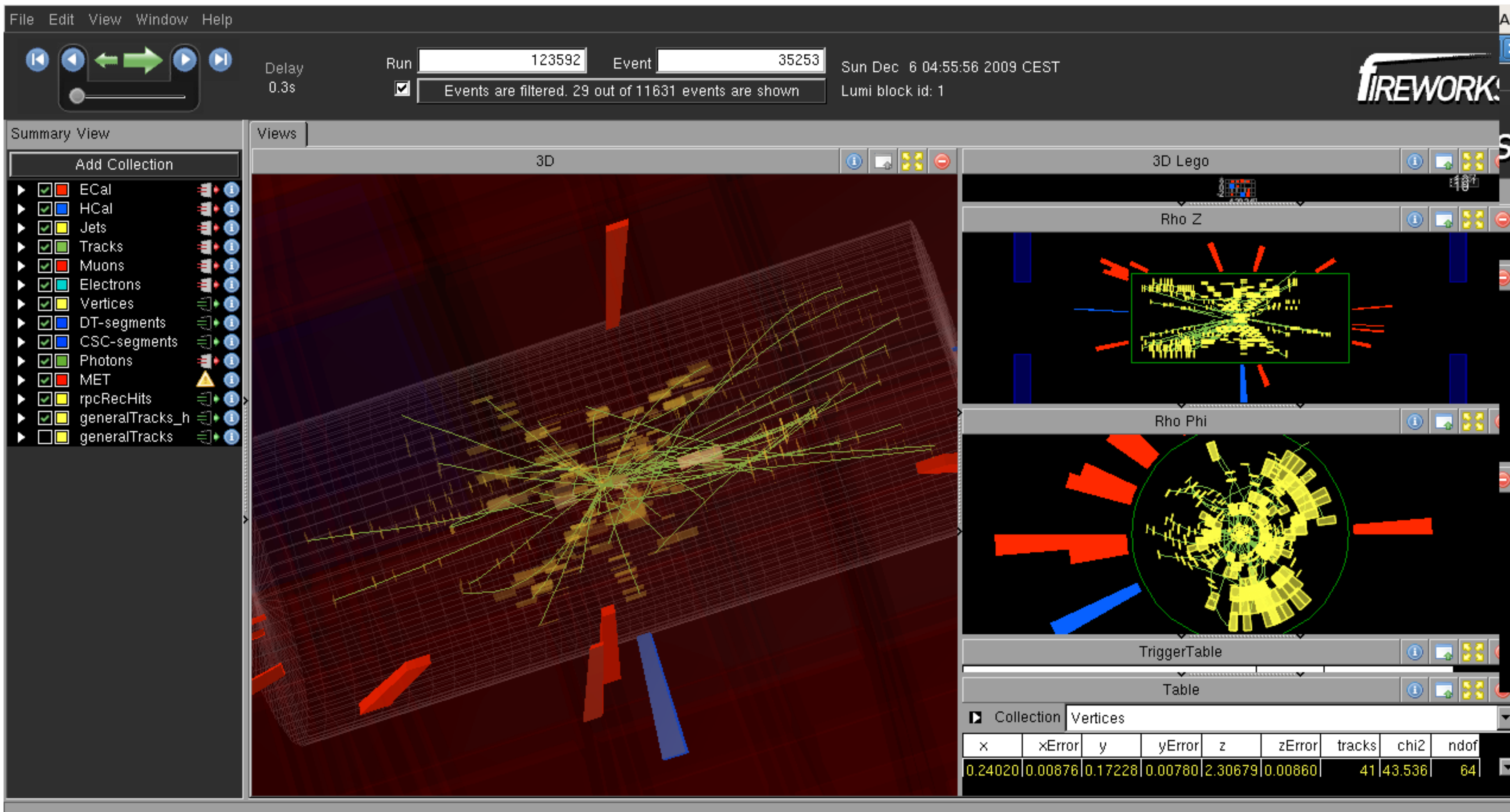
The momentum of the Higgs boson is the vector sum of the momenta of the 4 muons.

$\sqrt{E^2 - p^2c^2}$ will peak at the mass, mc^2, of the Higgs boson.

There are backgrounds like the copious production of ZZ^* that do not come from a Higgs.

LHC Status

- The LHC is currently operating at 7 TeV
- Rediscovering the known particles of nature.
- Establishing the background over which we can expect the signal for the Higgs boson and physics beyond the Standard Model.
- We should have statistically significant results of a discovery by next year.



Norse Creation Story: When the cold of Niflheim touched the fires of Muspell, the giant Ymir and a behemothic cow, Auohumla, emerged from the thaw.

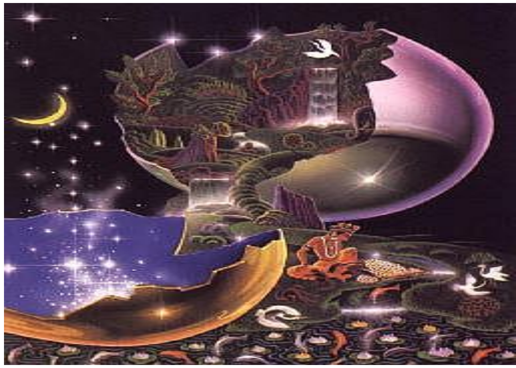
Zoroastrian Creation Story: Ahura Mazda creates a mountain Alburz which grew to touch the sky, bring rain and begin life.

An Egyptian Creation Story: Out of the chaos, Nun, arose Ra. Ra begot a pantheon of gods which were the earth, sky etc. Ra’s tears are humans.

In the Beginning…

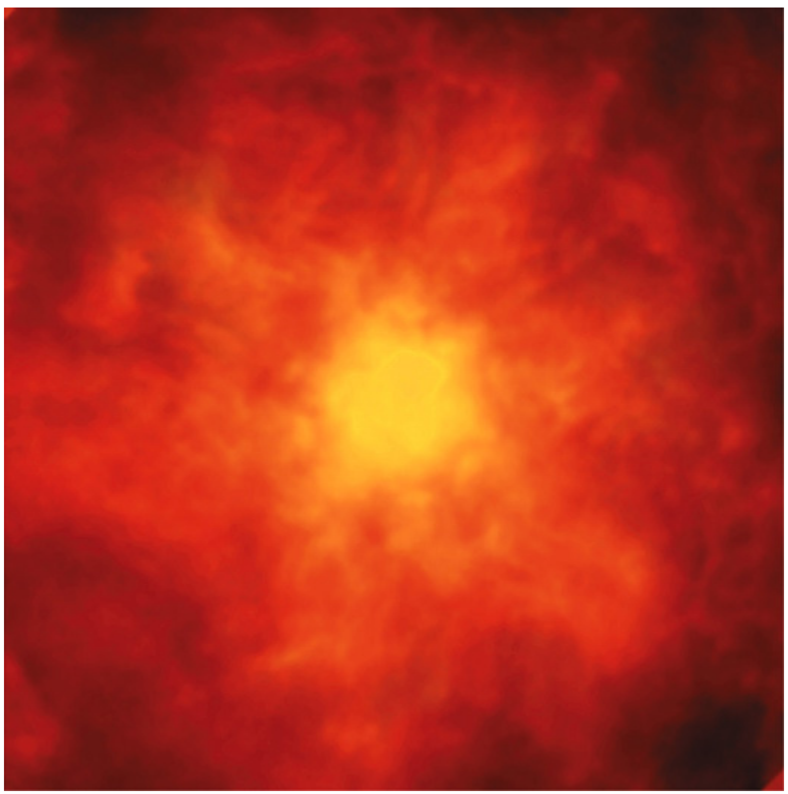
Judeo-Christian-Islamic Creation Story: In the beginning God created the heaven and the earth.

A Chinese Creation Story: Phan Ku hatched from an egg and grew for 18,000 years, pushing his shell apart into heaven and earth. Then he died and his remains became the sun and the moon. Humans are parasites on his body.



A Hindu Creation Story: Brahma hatched from an egg in the water and the remains of the egg became the universe.

There was a Bang

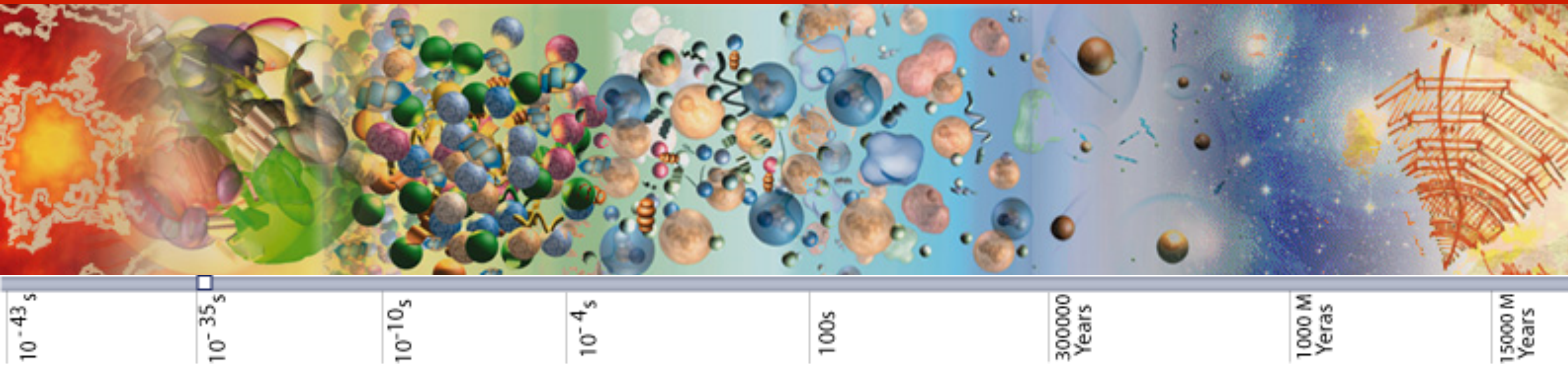


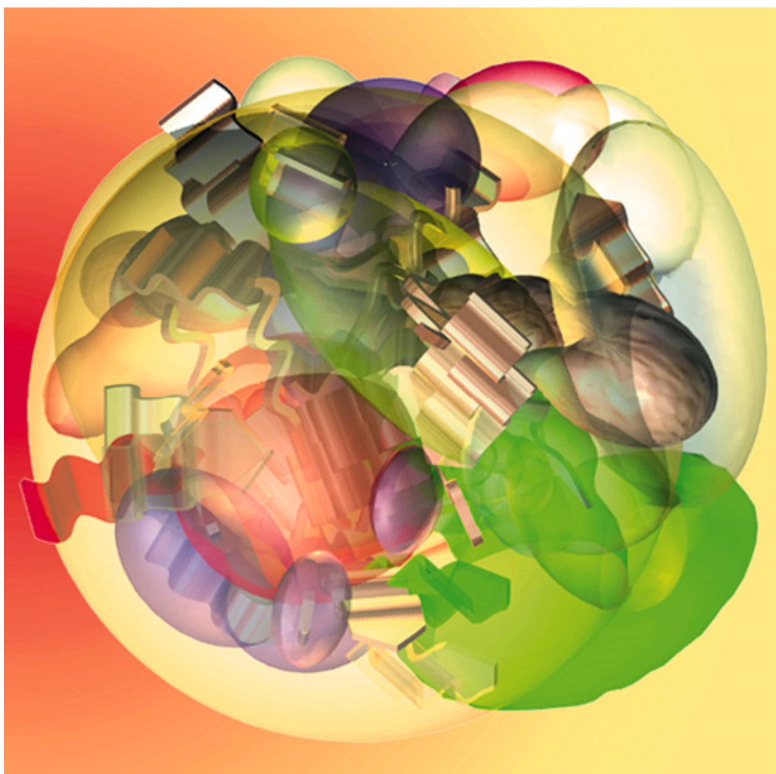
The Era of Quantum Gravity (10^{-43} sec, 10^{32} K)

• All particles, quarks, leptons, force carriers and other undiscovered particles existed in thermal equilibrium.

•Gravity “froze out” in a phase transition to be a force distinct from the strong nuclear, weak nuclear and electromagnetic forces by the end of this era.

In the Beginning... the Grand Unified Force degenerated





The Era of Inflation (10^{-35} sec, 10^{27} K)

• The universe *inflates* by a factor of 10^{50} in ~ 100 seconds. It reaches a total size of 10^{23} m.

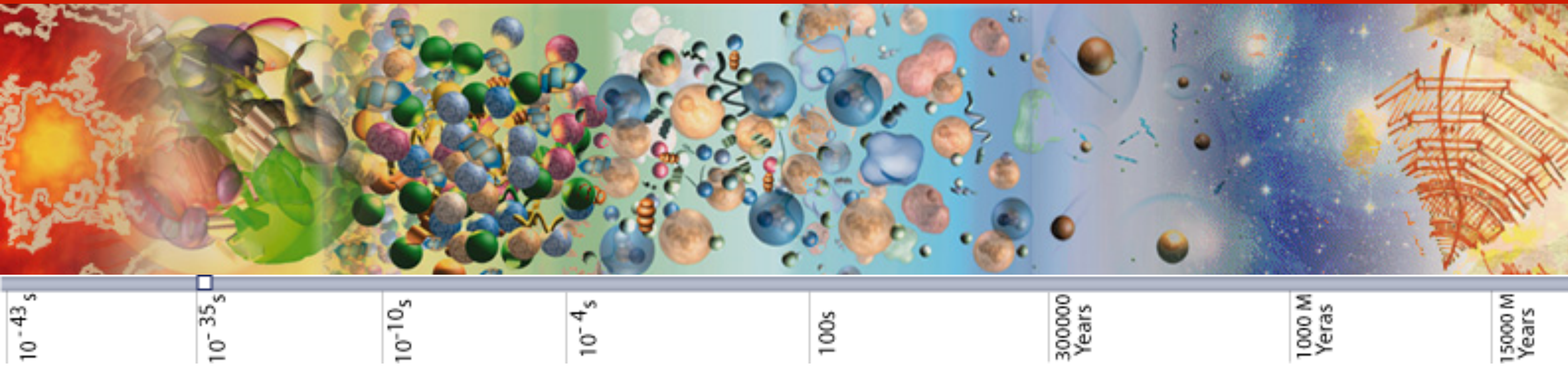
Degeneration of the Grand Unified Force
(10^{-32} sec)

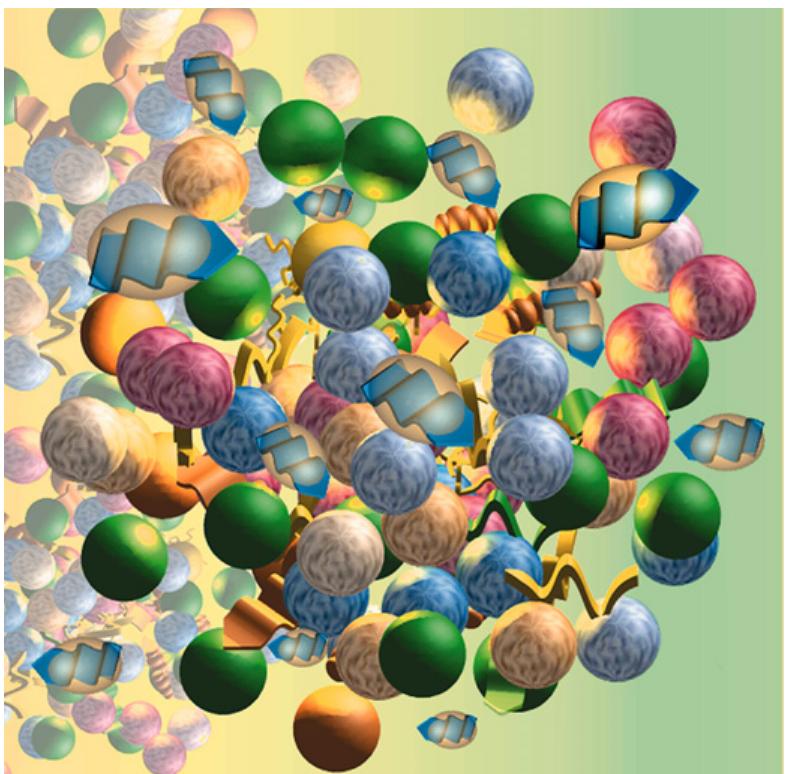
•The strong nuclear force "freezes out" as distinct from the electroweak force.

•A billion to one excess of matter over antimatter develops

(The LHC can reproduce this era!)

In the Beginning... the Electroweak Force degenerated





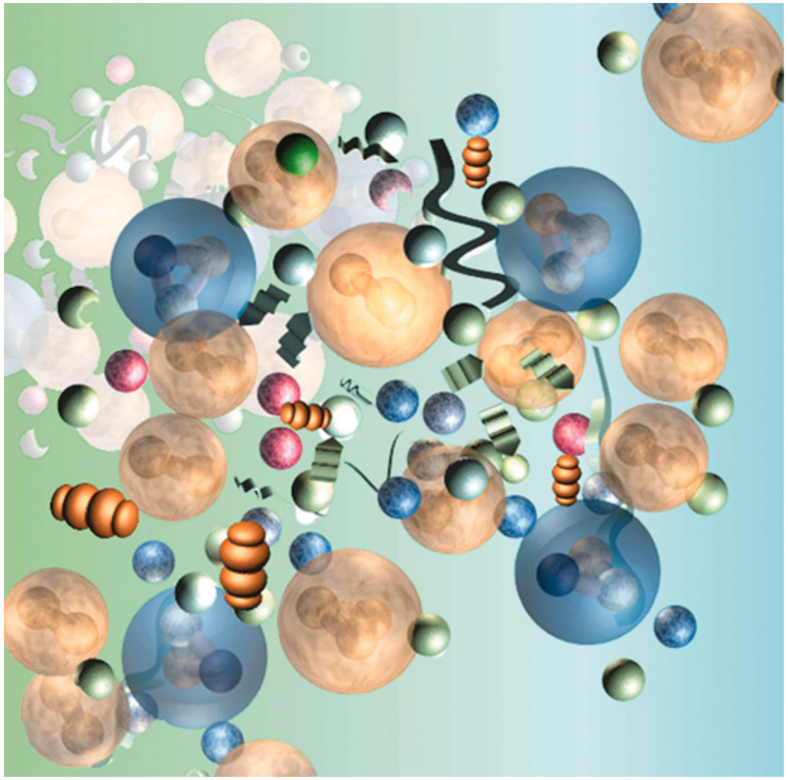
Electroweak Degeneration Era (10^{-10} sec, 10^{15} K)

• The weak nuclear force separates from the electromagnetic force. The W & Z bosons put on weight while the photon remains massless.

•Quarks annihilates with anti-quarks, leaving a tiny excess of quarks.

(These conditions have been reproduced and studied in previous experiments like the LEP)

Protons and Neutrons formed



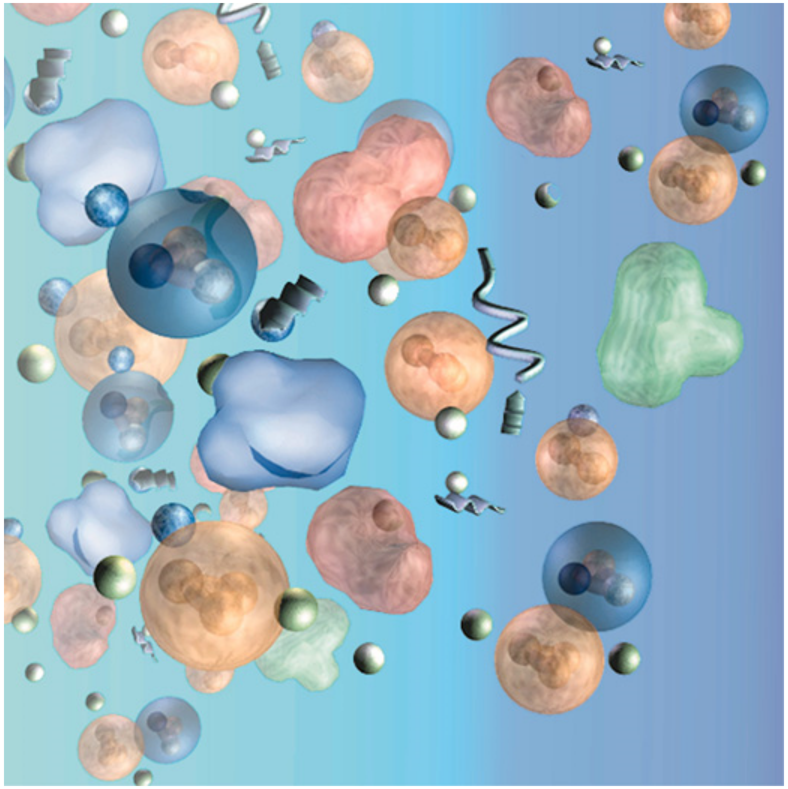
Protons and Neutrons form (10^{-4} sec, 10^{13} K)

• Quarks remaining from the annihilation bind with each other under the influence of the strong nuclear force to form protons and neutrons

Neutrinos decouple (10^{-4} sec, 10^{10} K)

•Neutrinos shy away from further interactions
•Electrons and positrons annihilate till a slight excess is left
•Neutron:Proton ratio shifts from 50:50 to 25:75

Atomic Nuclei formed

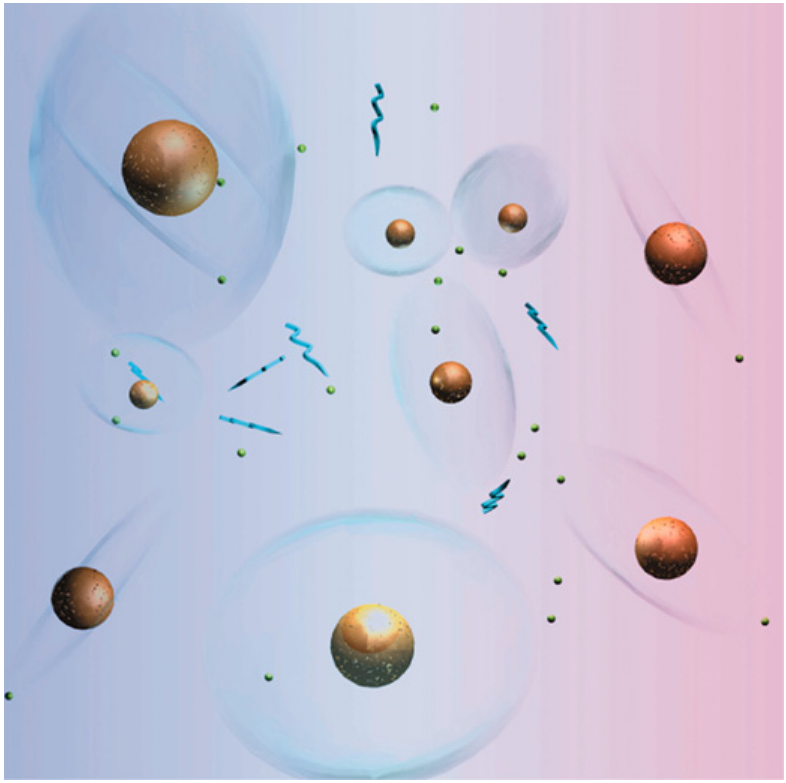


Helium Age (100 sec, 10^9 K)

• Helium nuclei can form now. Conditions similar to stars or hydrogen bombs.

•Atoms cannot form as yet.

Atoms formed and Light could travel freely

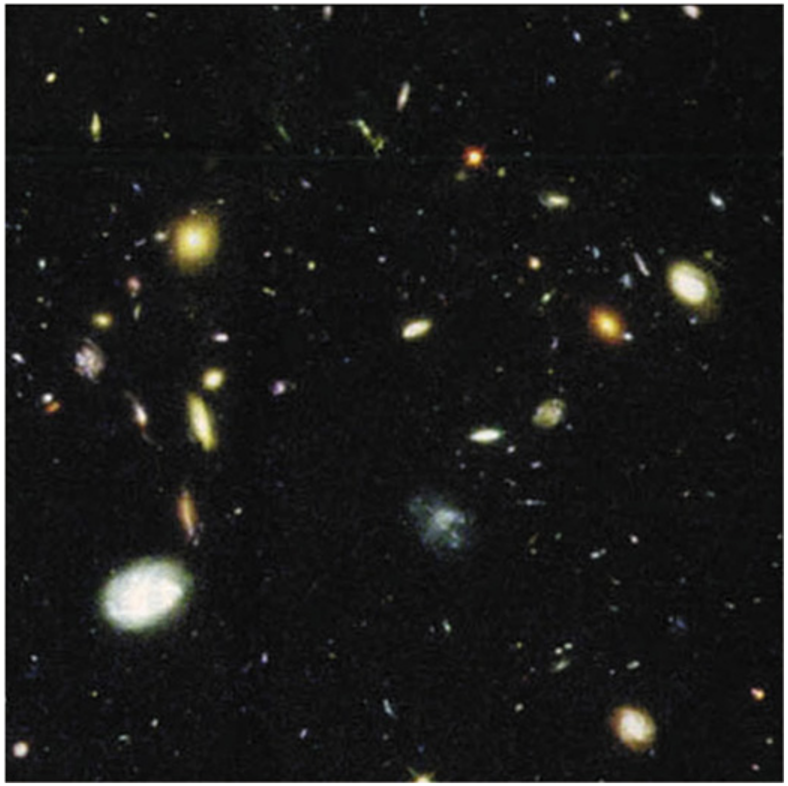


Atoms form (300,000 years, 6000 K)

• Light particles (photons) are not strong enough to break up atoms anymore. So, stable atoms of hydrogen and helium can form.

•The universe becomes transparent to radiation and finally there is light!

Stars and Galaxies formed

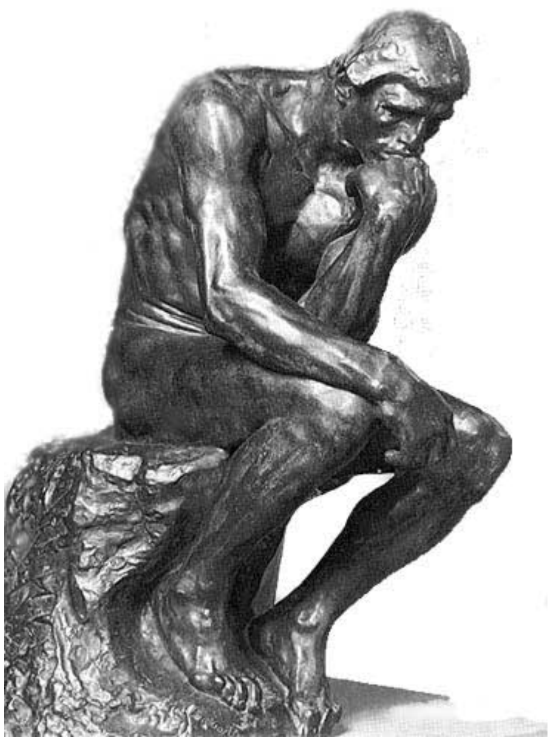


Stars and Galaxies form (1 billion years, 18 K)

• Stars begin to glow, turning lighter elements into heavier ones (of which planets and ourselves are going to be made of)

•Galaxies of stars begin to form

Life has arisen to soak in the Mystery



Today (13.7 billion years, 3 K)

• The dust of stars spewed out in supernovae explosions accumulate into planets

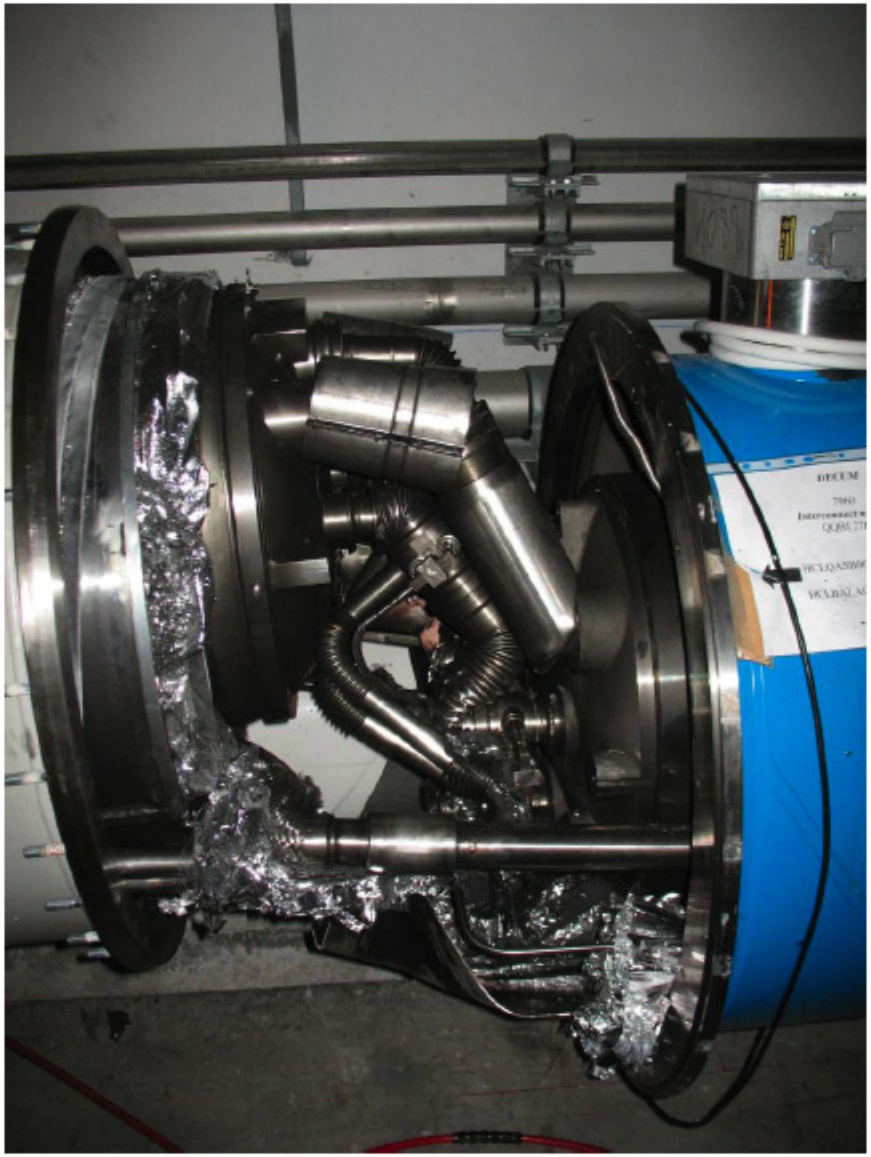
•Carbon atoms concatenate into complex molecules while the relentless energy from stars animate their ever-more-sophisticated dance of self-replication.

•And out of the stardust living creatures emerge to observe the universe and soak in the mystery

Backup Slides


"O Omnipresent, the embodiment of all virtues, the creator of this cosmic universe,
the king of dancers, who dances the Ananda Tandava in the twilight, I salute thee."
Presented by: The Department of Atomic Energy, Government of India.

19th September Malfunction



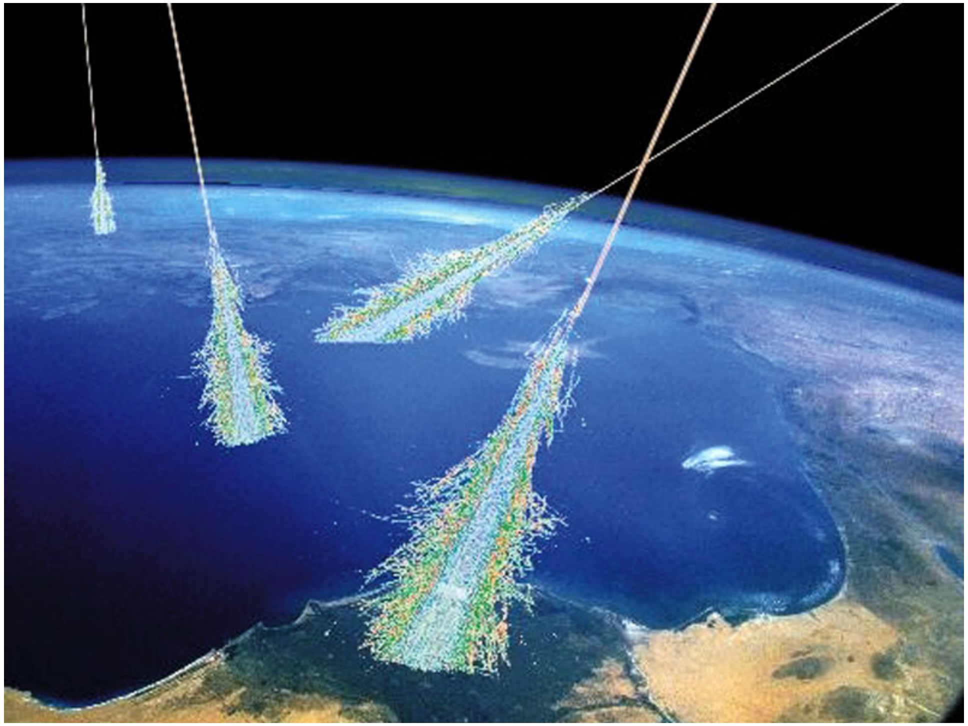
Repairs under way to be ready for physics by the *summer of 2009*

Life at CERN

Life at CERN

Is this Dangerous?

Cosmic Rays



The LHC collides particles with 14 TeV in the center of mass frame which corresponds to 10^{17} eV collision with a fixed target.

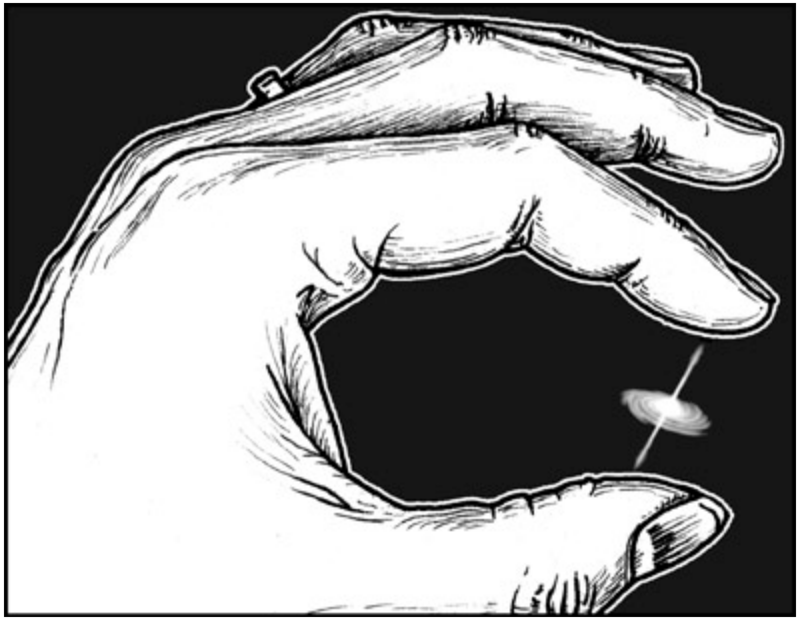
Cosmic rays from outer space routinely bombard the earth and its atmosphere with up to 10^{20} eV.

3×10^{22} cosmic rays with energies above 10^{17} eV are estimated to have collided with the earth since its formation.

The LHC running over 10 years have been repeated billions of times in the sun already!

Is this Dangerous?

Microscopic Black Holes



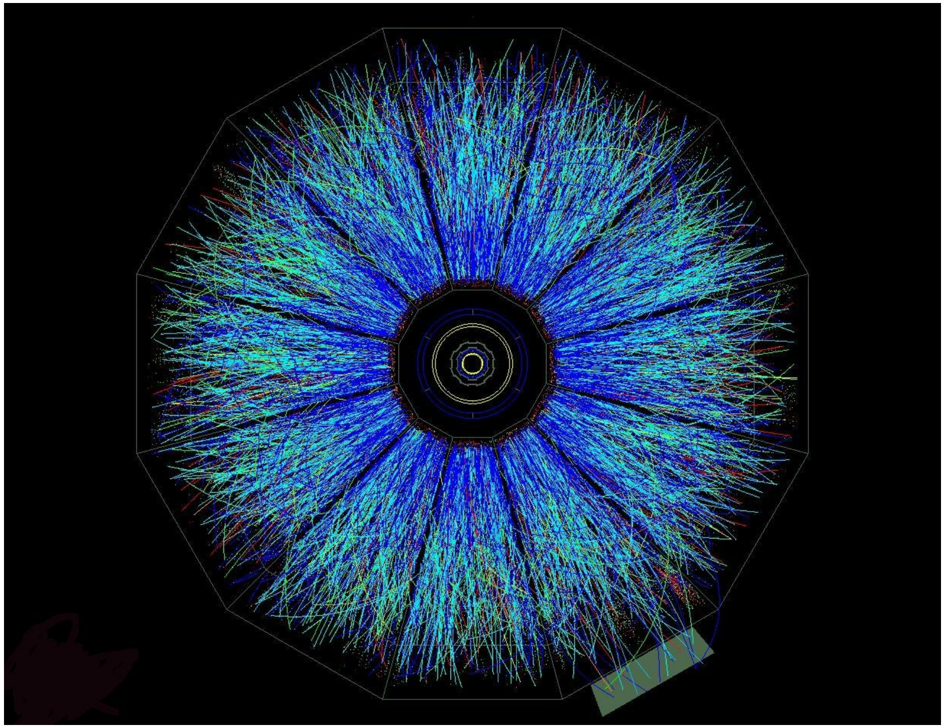
Some speculative theories predict the formation of microscopic black holes at the LHC.

All these theories also predict instantaneous evaporation of such black holes into showers of particles.

No time to accrete matter.

Is this Dangerous?

Strangelets

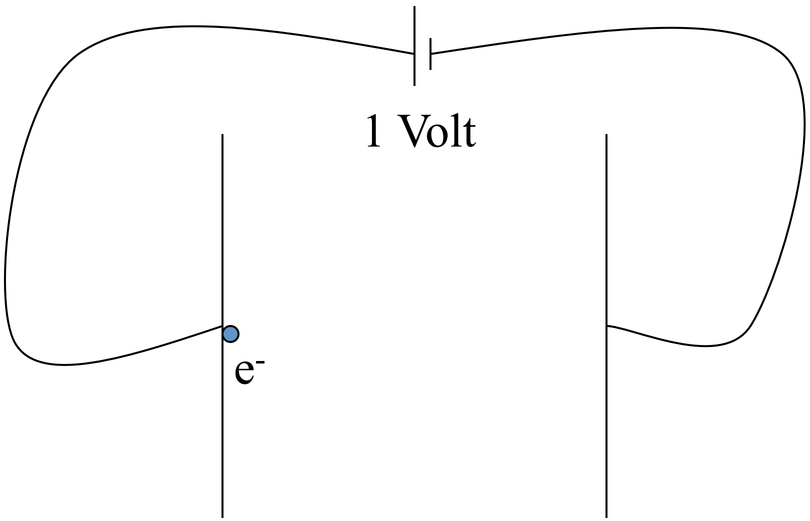


Strangelets are highly speculative conglomerations of equal amounts of up, down and strange quarks which may be stable.

Never observed in nature or in heavy ion collision experiments at the Relativistic Heavy Ion Collider.

Probability of forming strangelet decreases with increase in collision energy. LHC has higher energy collision than RHIC.

Mass and Energy in Electron Volts



1 eV = kinetic energy gained by an electron when it accelerates through an electrostatic potential of 1 volt

$$1 \text{ eV} = 1.6\times10^{-19} \text{ J}$$

Einstein's mass-energy equivalence allows us to quote mass in terms of energy.

The mass of subatomic particles are quoted in eV, MeV (million electron volts), GeV (billion electron volts) and TeV (thousand billion electron volts).

$$\text{mass of a proton} = 1.67\times10^{-27} \text{ kg} = 938 \text{ MeV}/c^2 \approx 1 \text{ GeV}$$