

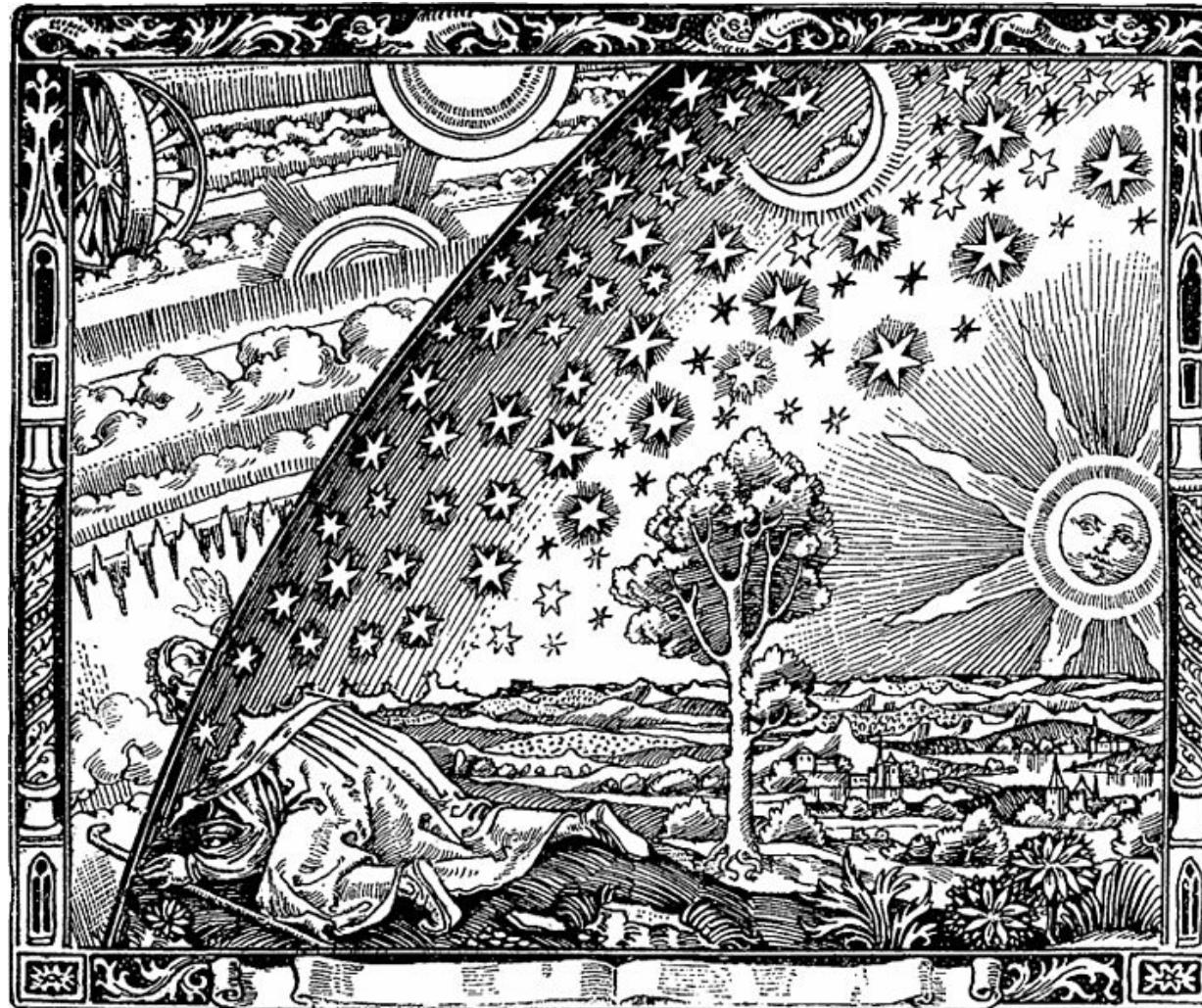


The Large Hadron Collider and Particle Physics

Discovering the Higgs
Boson and Looking Beyond

Souvik Das

CERN – European Centre for Nuclear Research



Between 2010 and 2012, humanity peered deeper into Nature
... and watched the gears turn.

CERN – European Centre for Nuclear Research

In one of the world's **biggest** laboratories,



CERN – European Centre for Nuclear Research

in the world's **fastest** and most **brutal** racetrack,

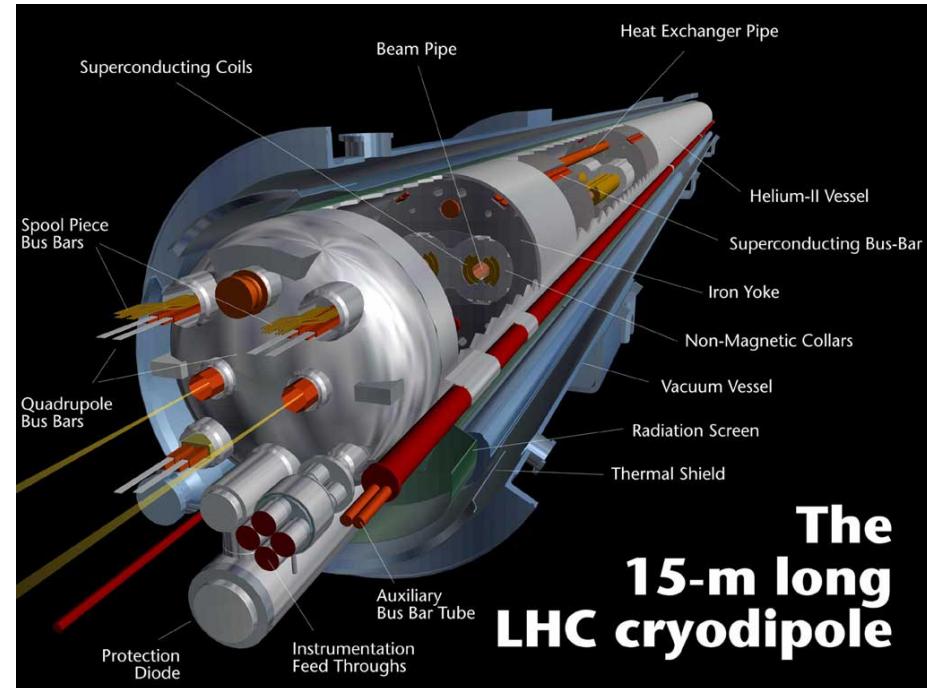
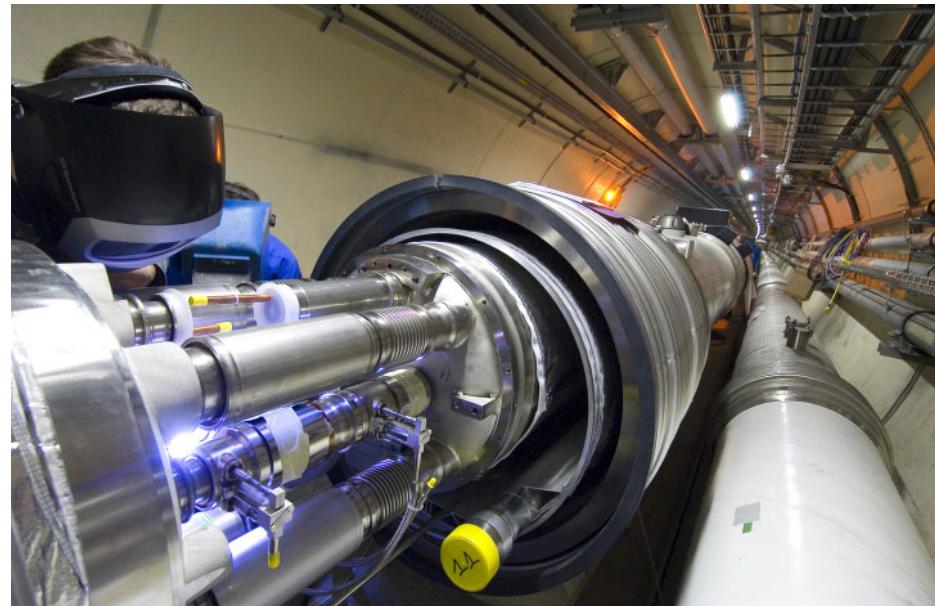


Protons raced
around a 27 km
circuit at
99.99999%
the speed of
light,

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

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



The beam pipe is evacuated to the same vacuum as interplanetary space
The pressure is about 1/10th that of the surface of the moon.

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

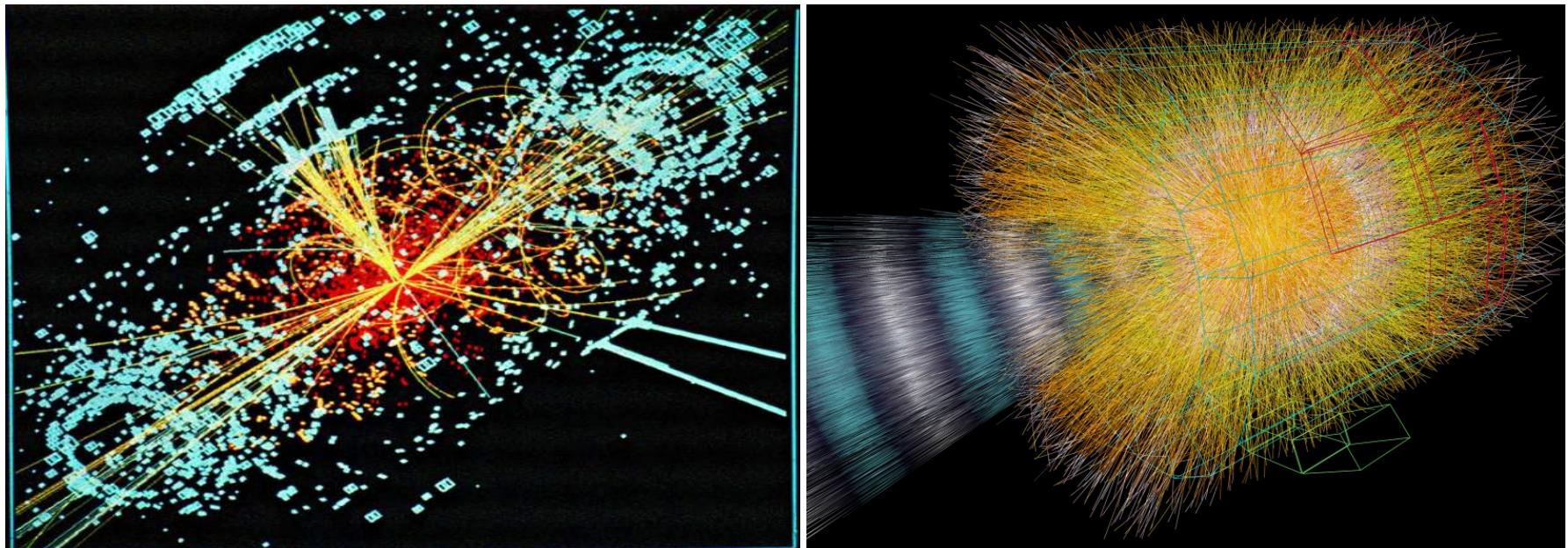


Superconducting and superfluid liquid helium is maintained at -271.3 C or 1.9 K.

That is a little colder than interstellar space.

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we produced 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

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that we watched with the **most complex** “eyes” ever built,

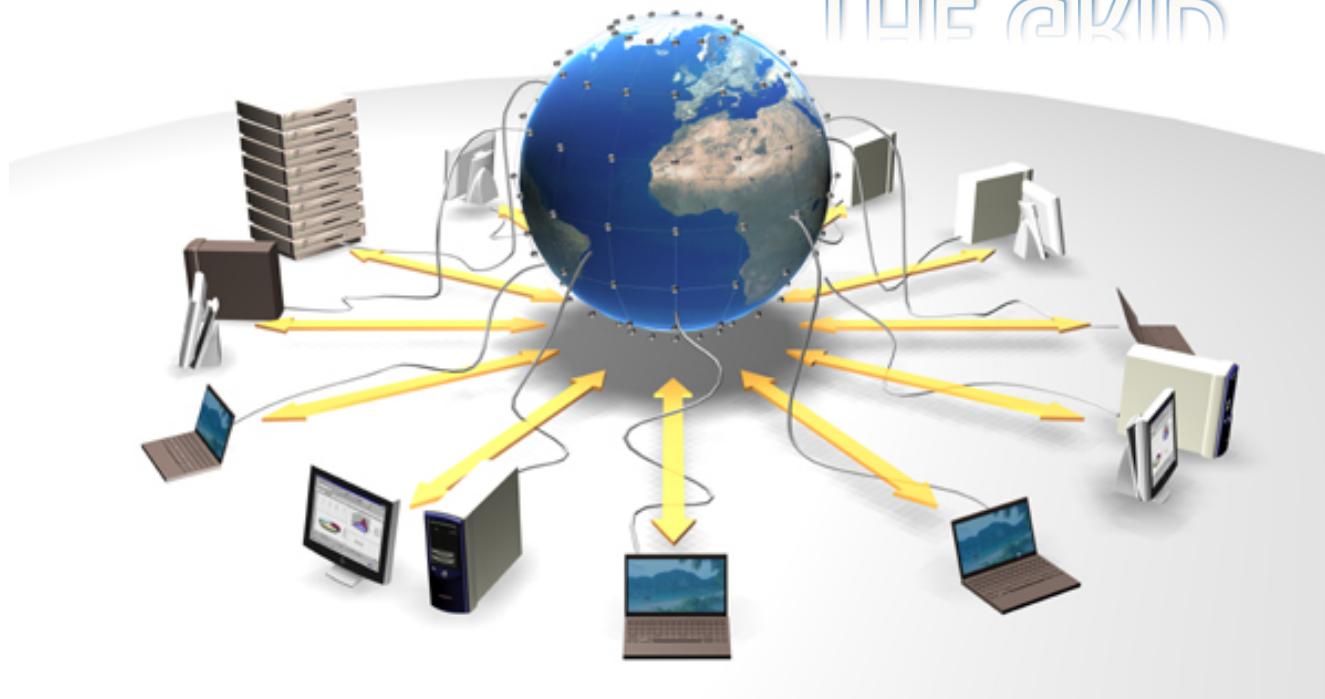


The detectors together have 140 million data channels observing at 40 million times a second.

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and analyzed with the most **powerful** computing system in the world

THE GRID



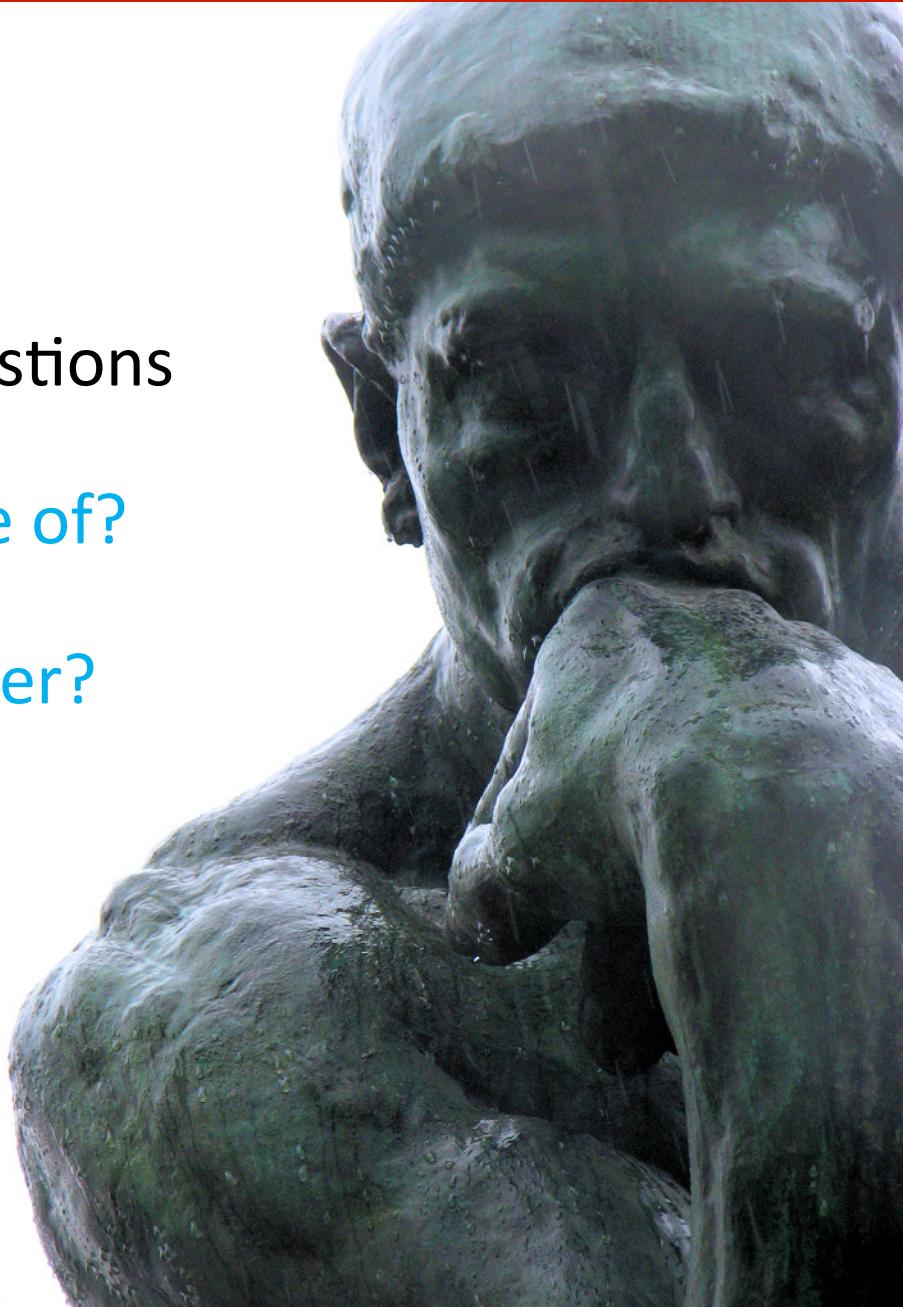
The detectors spewed out analyzed data at **700 MB/sec.**

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

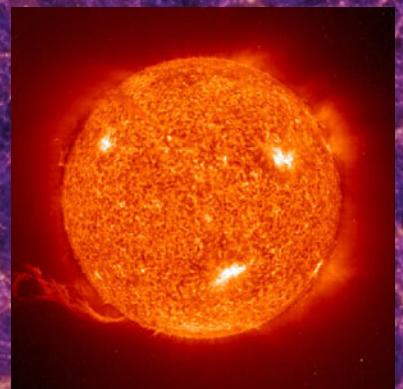
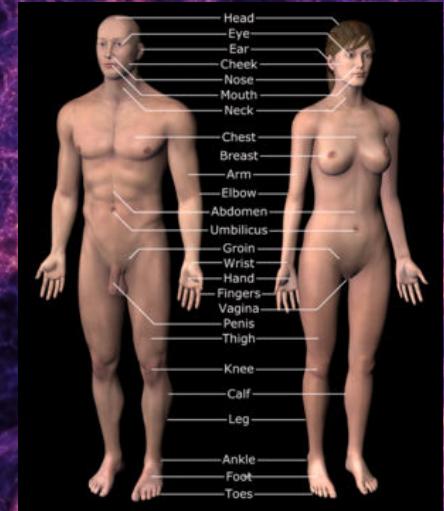
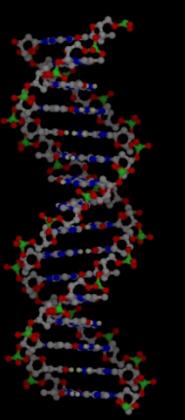
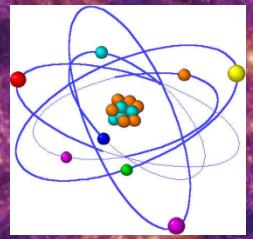
Particle Physics a.k.a. High Energy Physics

to answer the ancient questions

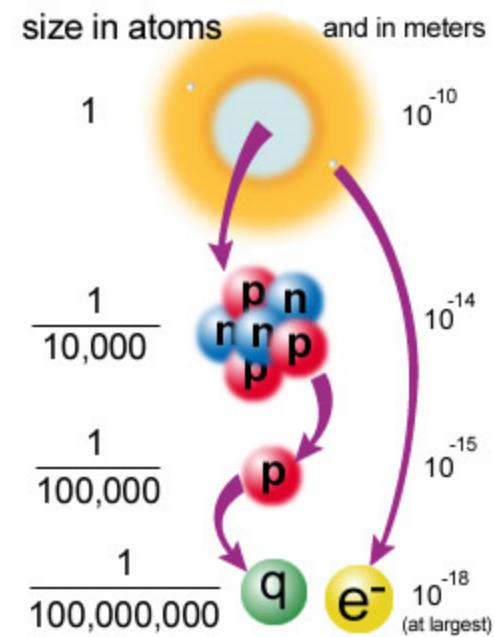
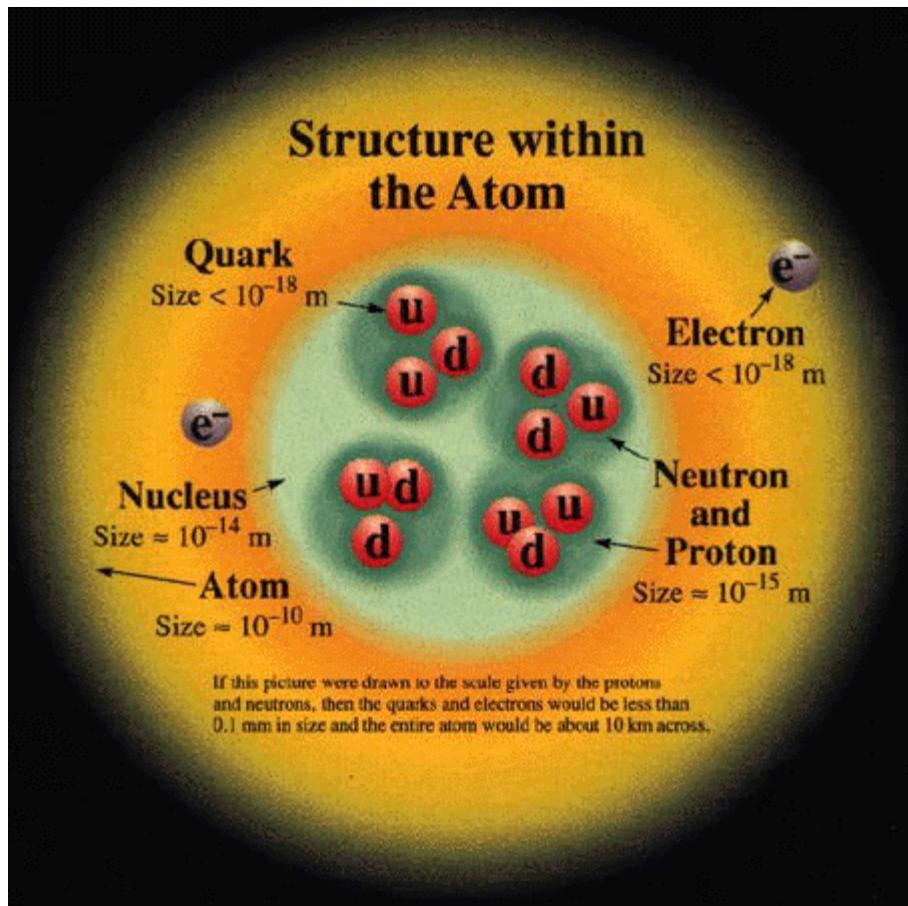
1. What is everything made of?
2. What holds it all together?



What is everything made of?



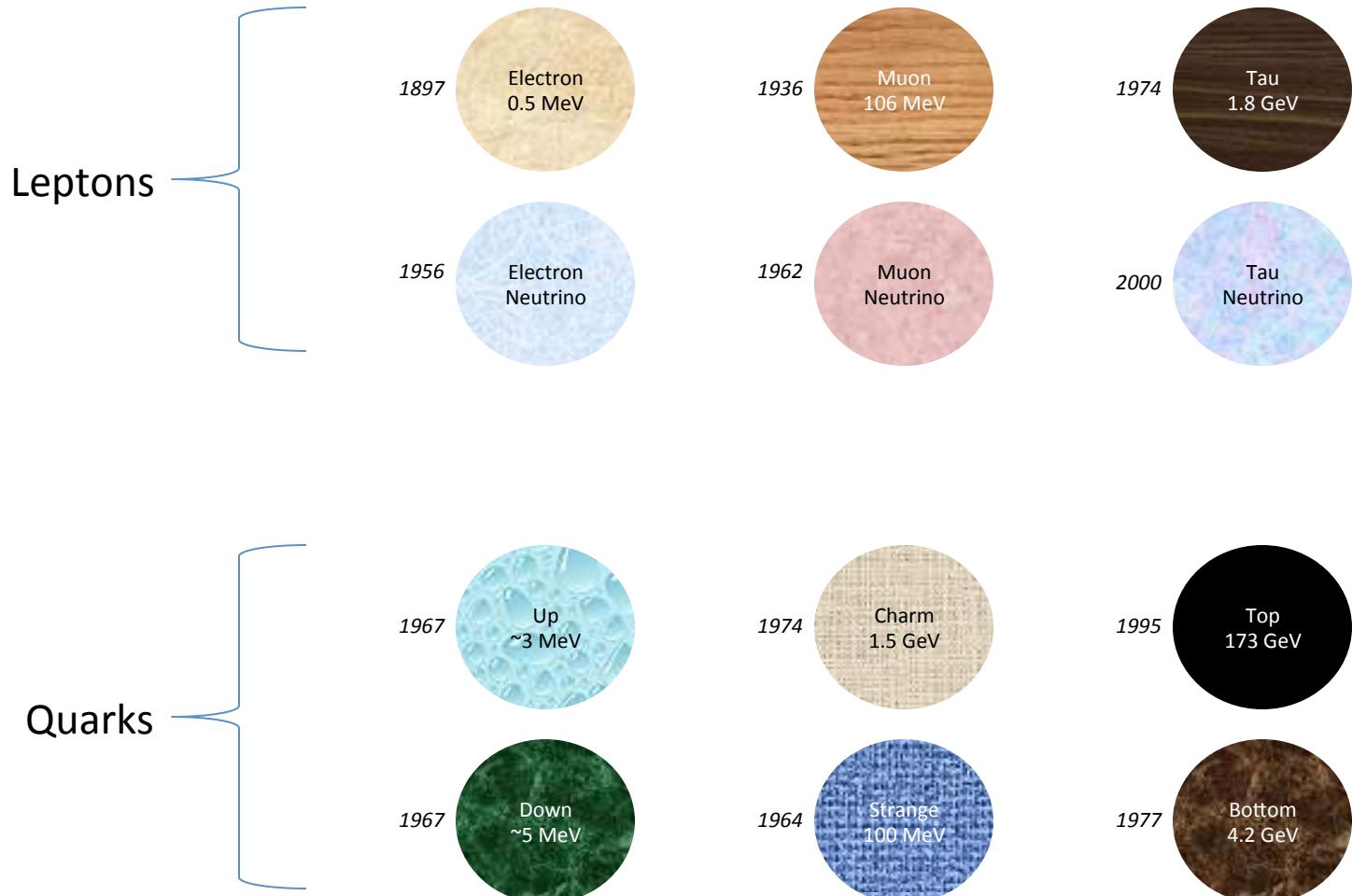
What is everything made of?



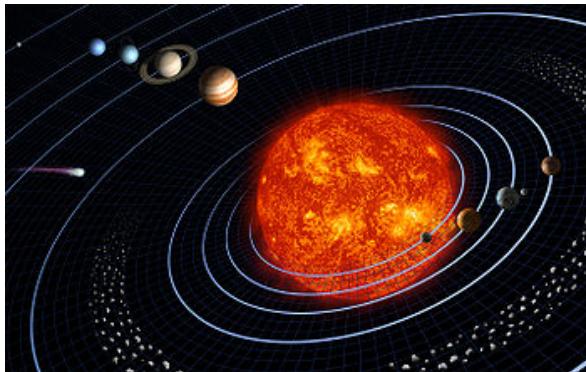
*By convention there is colour,
By convention sweetness,
By convention bitterness,
But in reality there are atoms and space.
- Democritus (400 B.C.)*

What is everything made of?

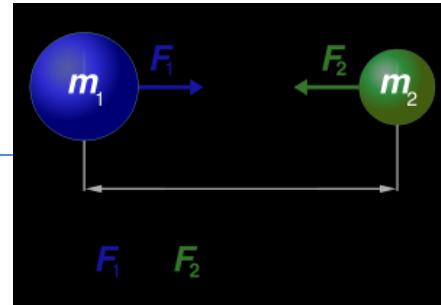
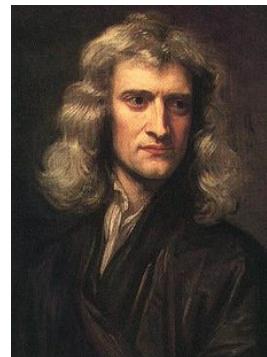
Why 3 generations? No one really knows!



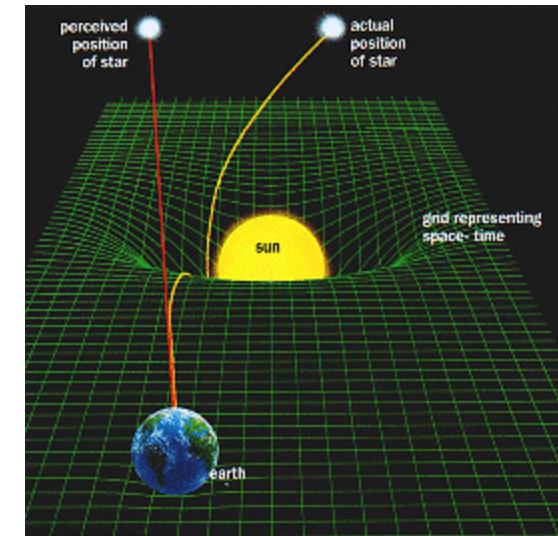
What holds everything together? – (I) Gravitation



Celestial Gravitation



**Newton's Law of
Universal
Gravitation**

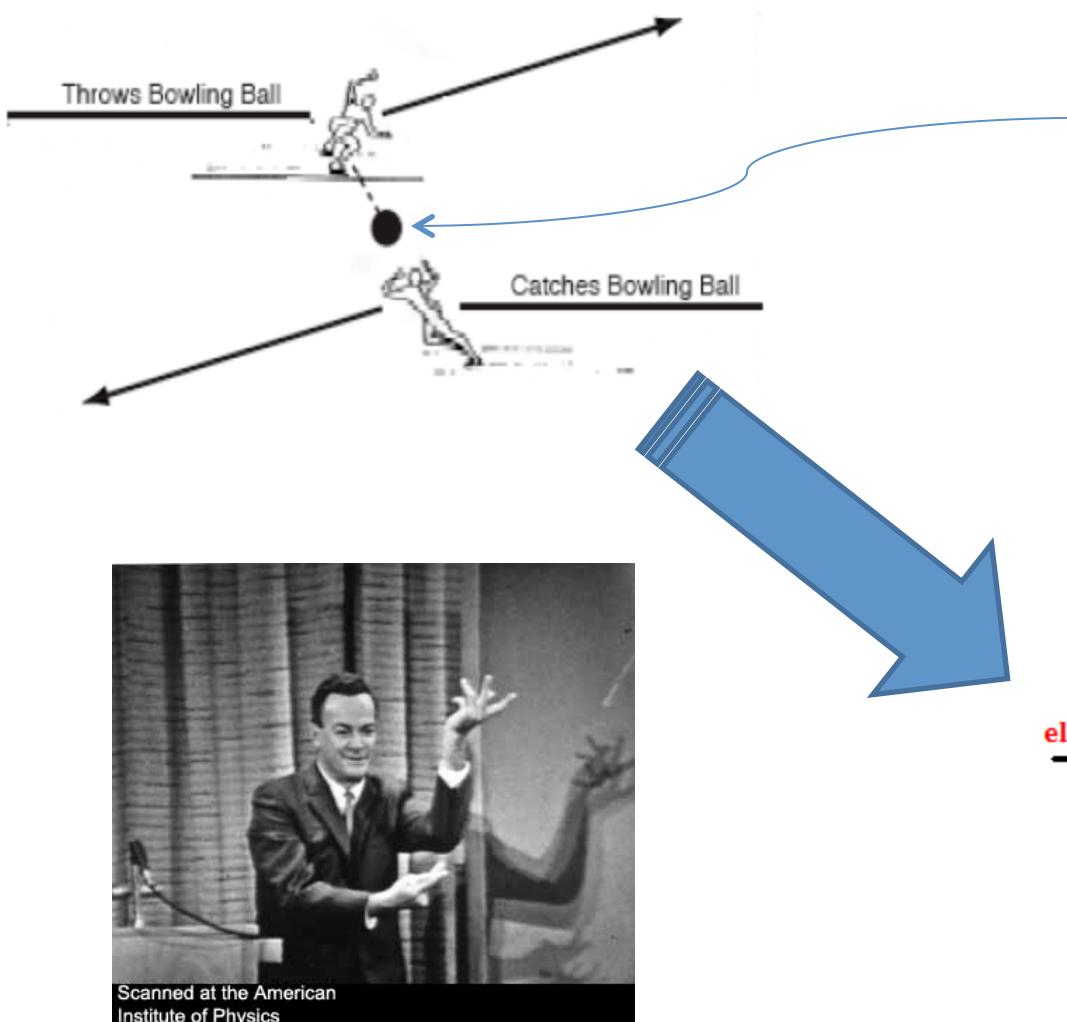


**Einstein's
General Theory of
Relativity**

Terrestrial Gravitation

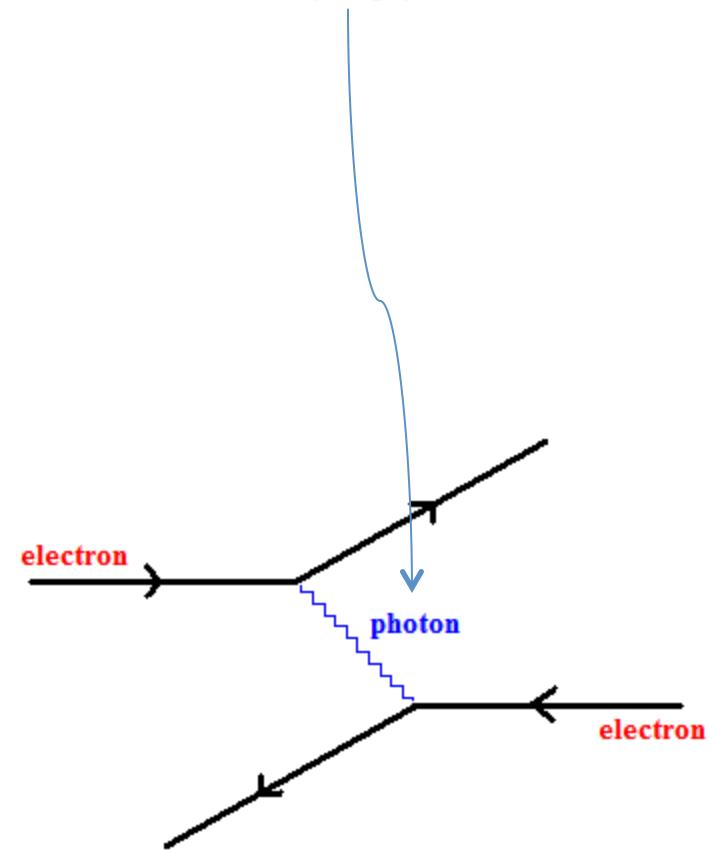
Forces as Interactions

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



Richard Feynman

All forces are mediated by a **force-carrying particle**.

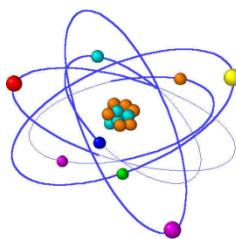


A **Feynman Diagram** for two electrons repelling each other

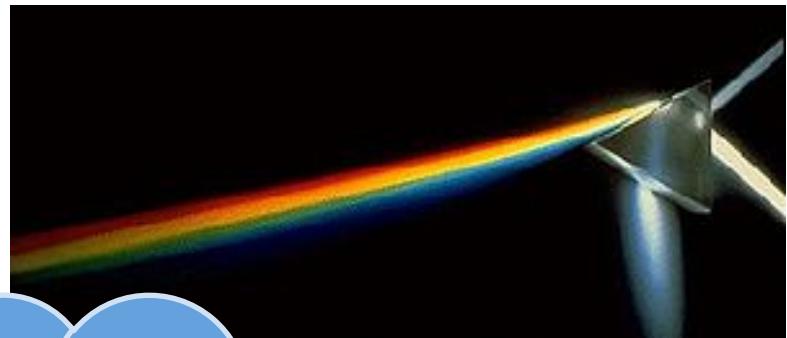
What holds everything together? – (II) Electromagnetism



Electricity



Chemistry



Light

The Electromagnetic Force

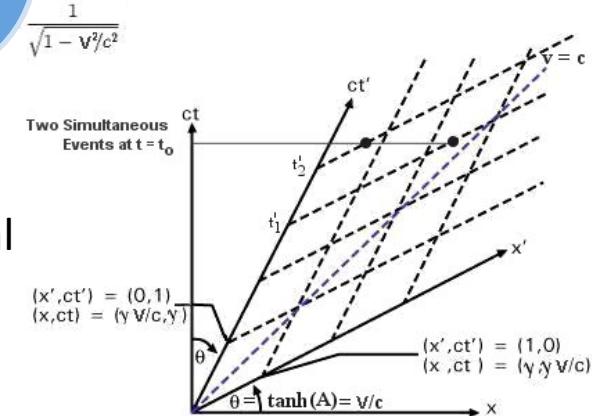
- Felt by all charged particles
- Carried by particles called *photons* in the quantum theory



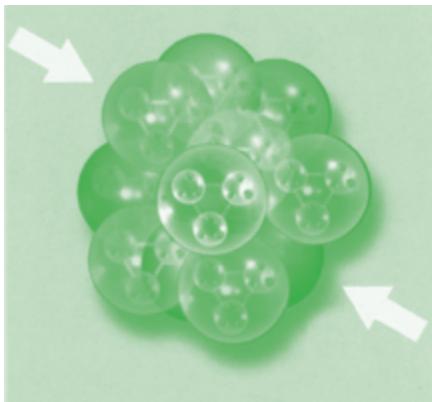
Magnetism

Photon
0 mass

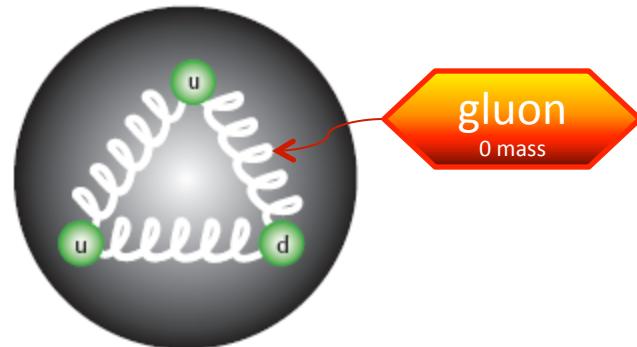
4 dimensional
space-time



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



Binds protons and neutrons together to form atomic nuclei

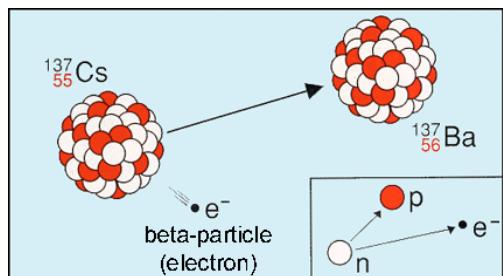


Binds quarks together to form protons and neutrons

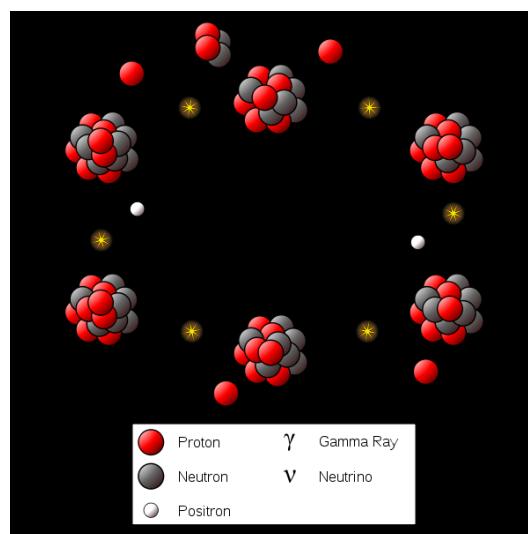
The Strong Nuclear Force

- Operational inside neutron stars and other exotic matter
- Mediated by particles called *gluons*
- Quarks and other gluons feel this force
- Very short in range

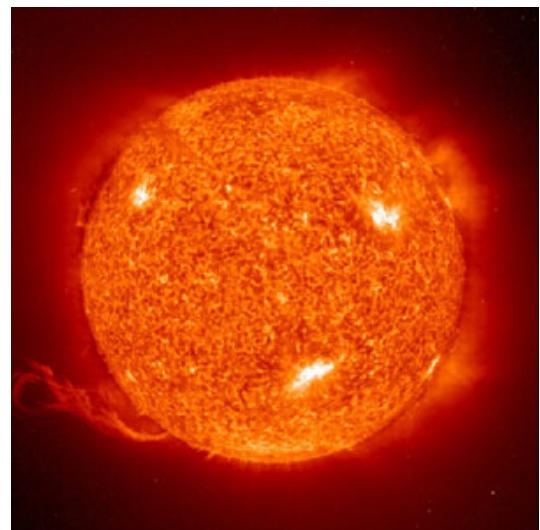
What holds everything together? – (IV) Weak Nuclear Force



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

Electricity
Magnetism

Electromagnetism

Photon
0 mass

Weak Nuclear Force



Electroweak
Force
0 mass

But this theory predicts a
new undiscovered particle!



Strong Nuclear Force



Celestial Gravitation

Terrestrial Gravitation

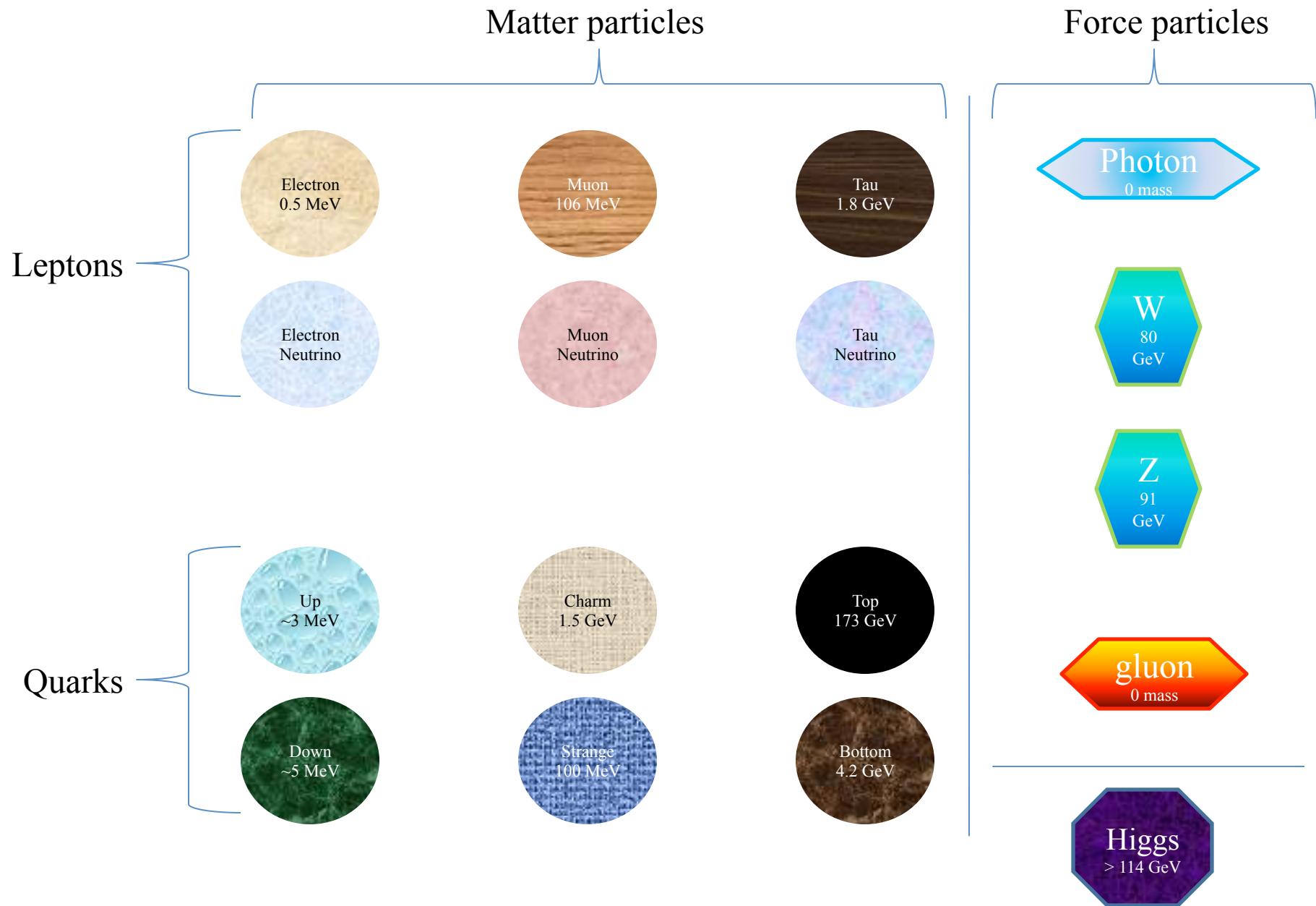
Universal
Gravitation

General
Theory of
Relativity

No battle tested
quantum
theory yet!

**Grand Unified
Force**
(Too many
theories,
none tested!)

The Standard Model of Particle Physics



The Higgs Boson – Breaking Electroweak Symmetry



- The **Glashow-Salam-Weinberg** theory of Electroweak Unification:
 - Places the the γ , W and Z on the same footing as **symmetrical cousins**.
 - Accurately predicts the ratio of masses of the W and Z bosons in terms of the strengths of the electromagnetic and weak forces.
 - Requires a mechanism to **break the symmetry** to lend the W and Z mass
- The Higgs mechanism is the simplest mechanism to **break electroweak symmetry**.
- Generates **a new particle** that is the Higgs boson.
- The interaction strength between the Higgs and other fields are set theoretically but its mass is not. Its **mass has to be determined experimentally**



The Higgs Boson – Generating Mass

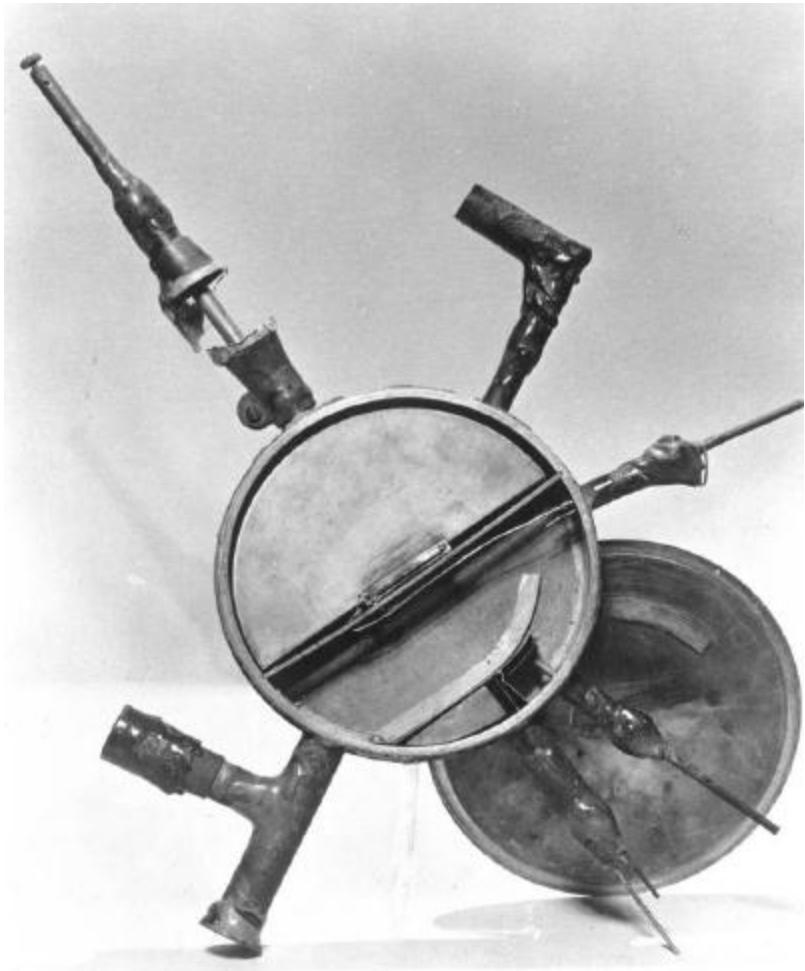


- The Higgs field gives the W and Z mass through Electroweak Symmetry Breaking
- But the mathematical structure of the Higgs also allows it to give **mass to the matter fields**, by interacting with them

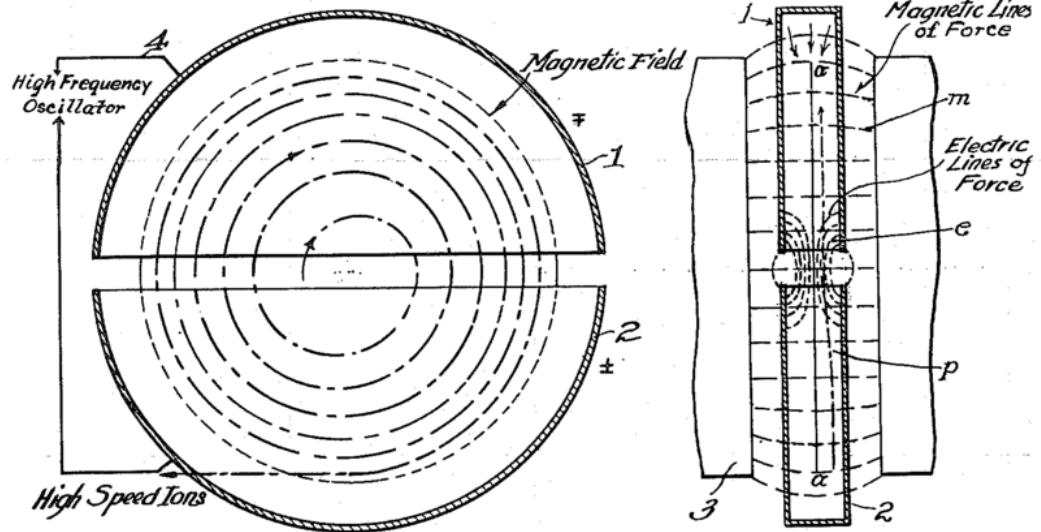
One elegant solution to two problems!

The Higgs boson does not contribute any significant mass to protons or people

The Particle Accelerator



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

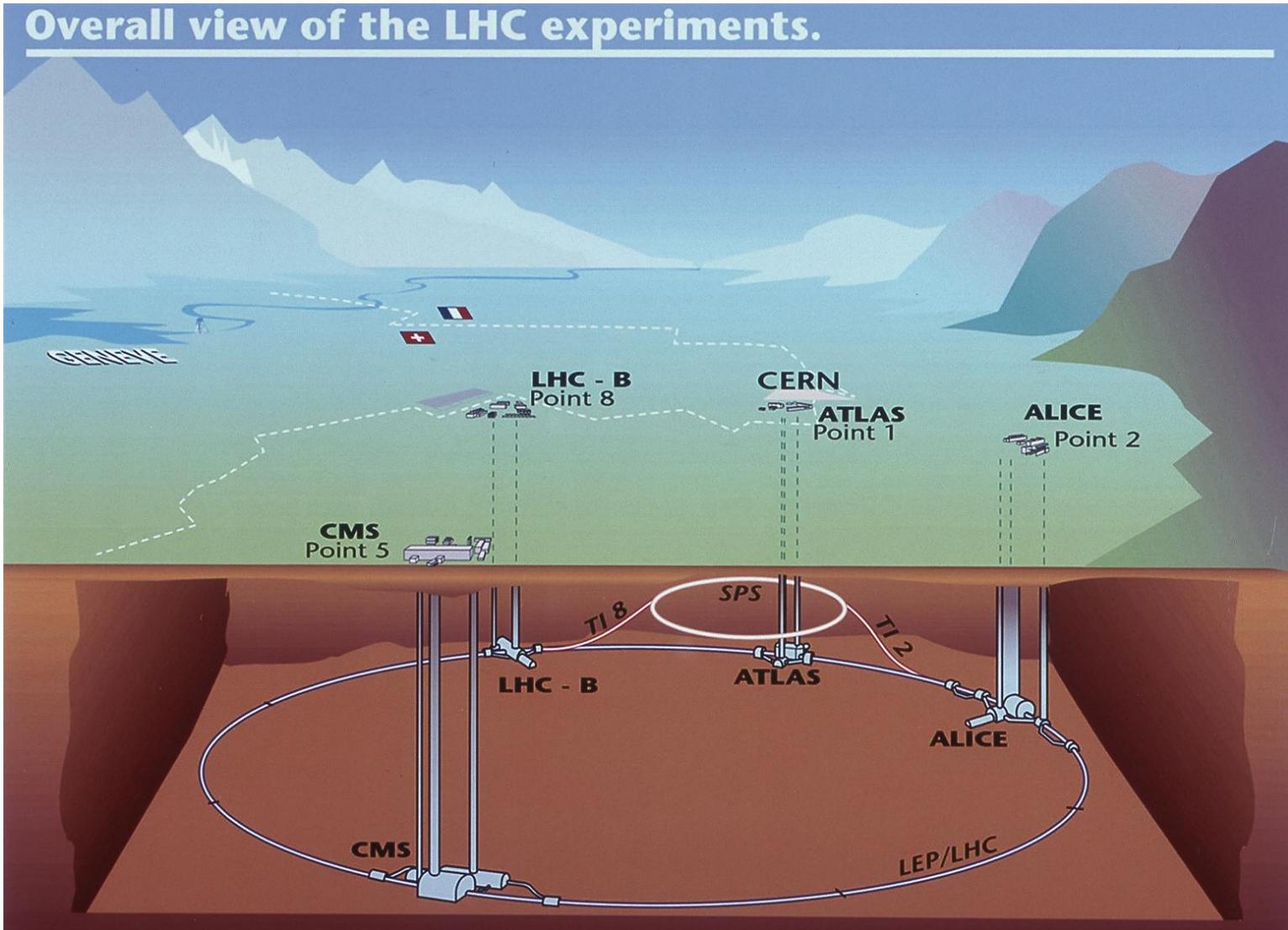


The patent to the first particle accelerator (cyclotron) developed by Ernest O. Lawrence in 1929

- 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?

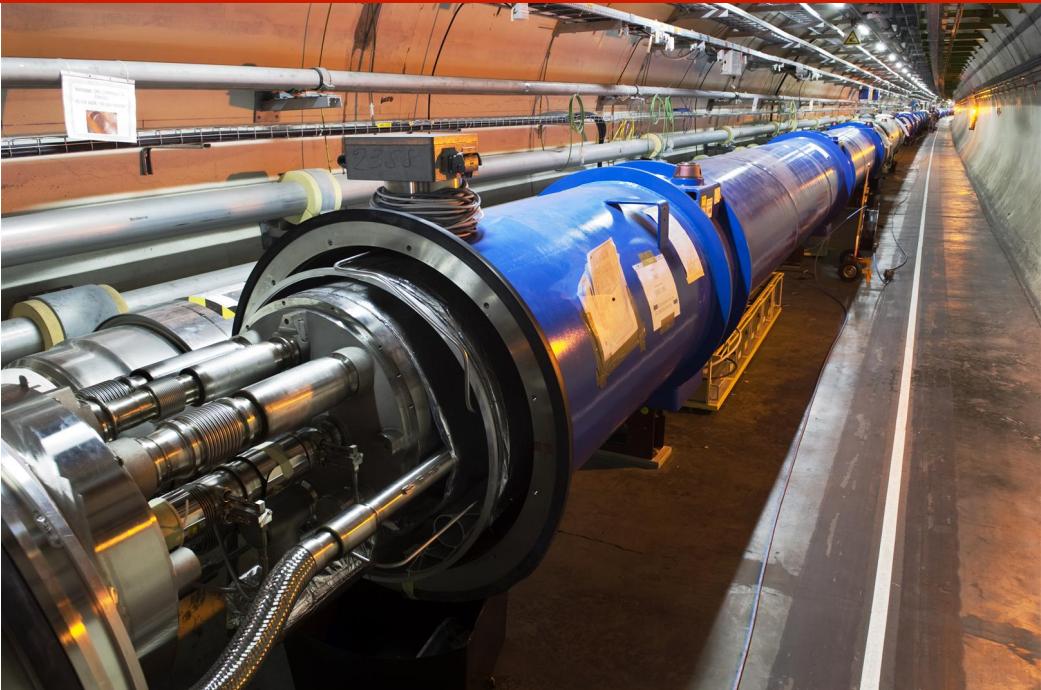
The Particle Accelerator

Overall view of the LHC experiments.



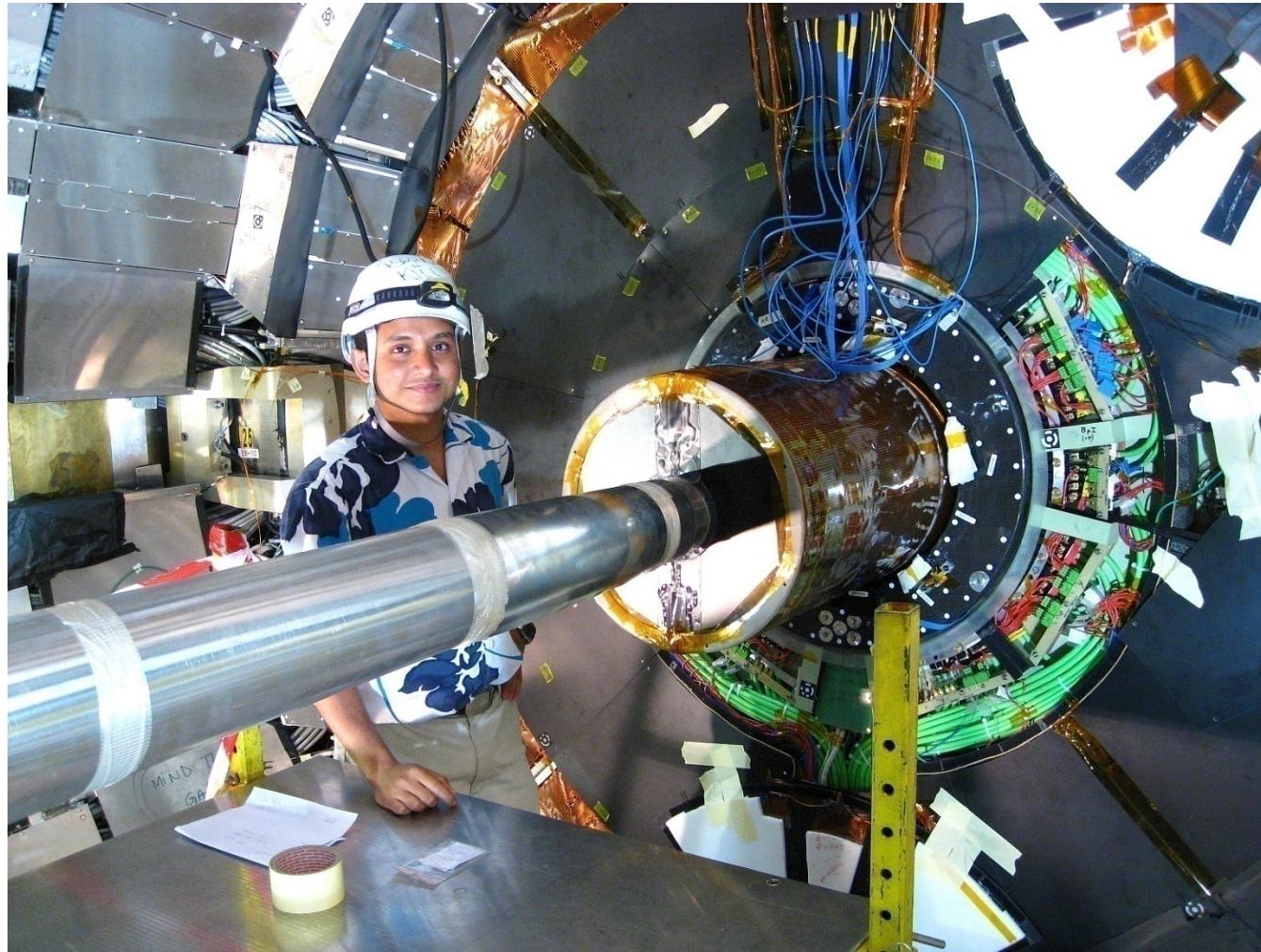
- 100 m below the surface
- 27 km in circumference

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.

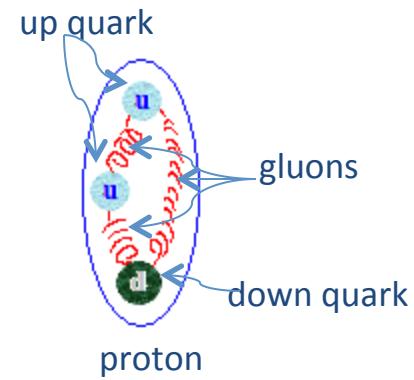
The Particle Accelerator



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.

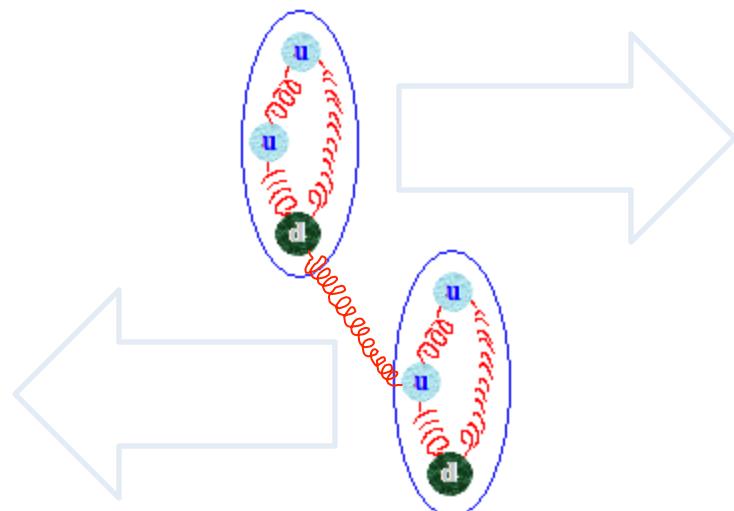
Collision Point



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

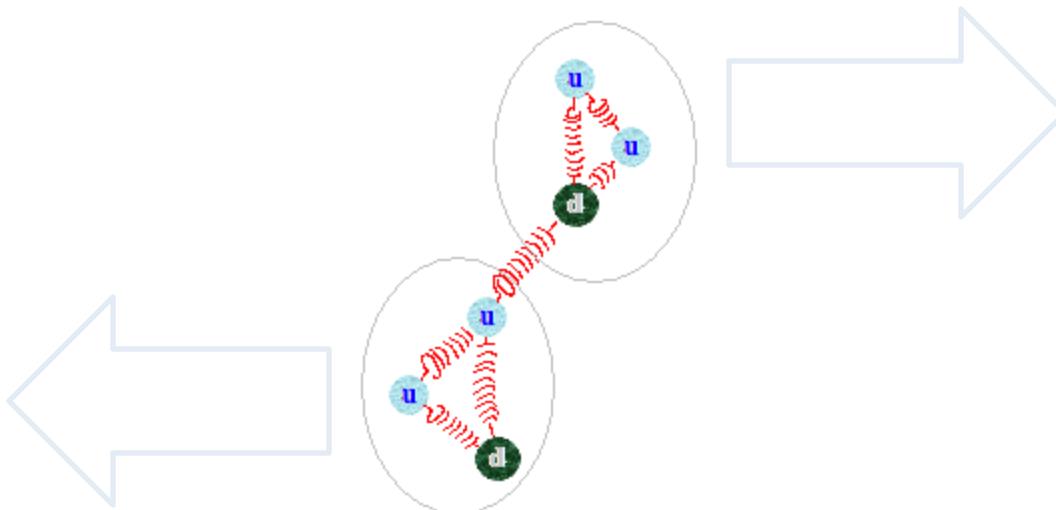
The energy allows them to overcome their mutual electromagnetic repulsion and **allows their quarks and gluons to interact** via the strong nuclear force.

The Crash – Approach



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

The Crash – Interaction



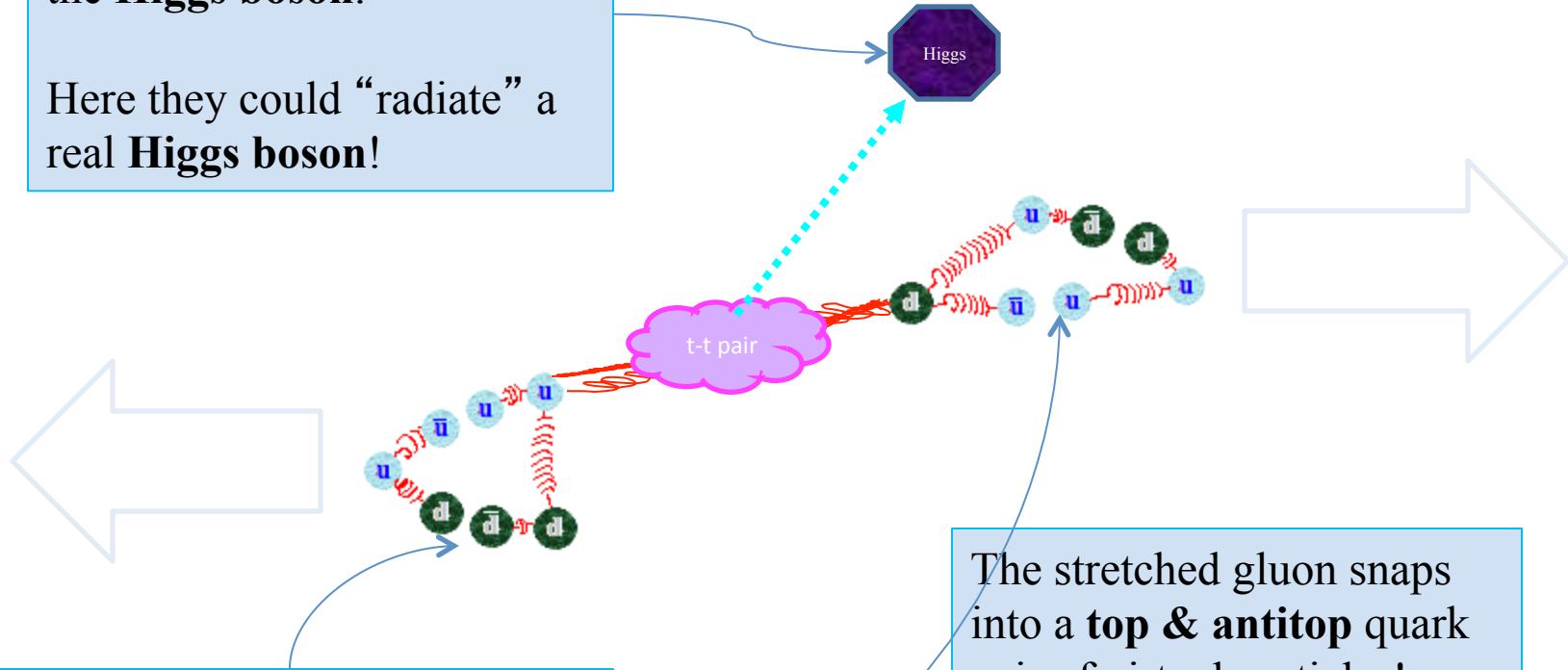
The newly formed gluon is under high tension now!

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**!

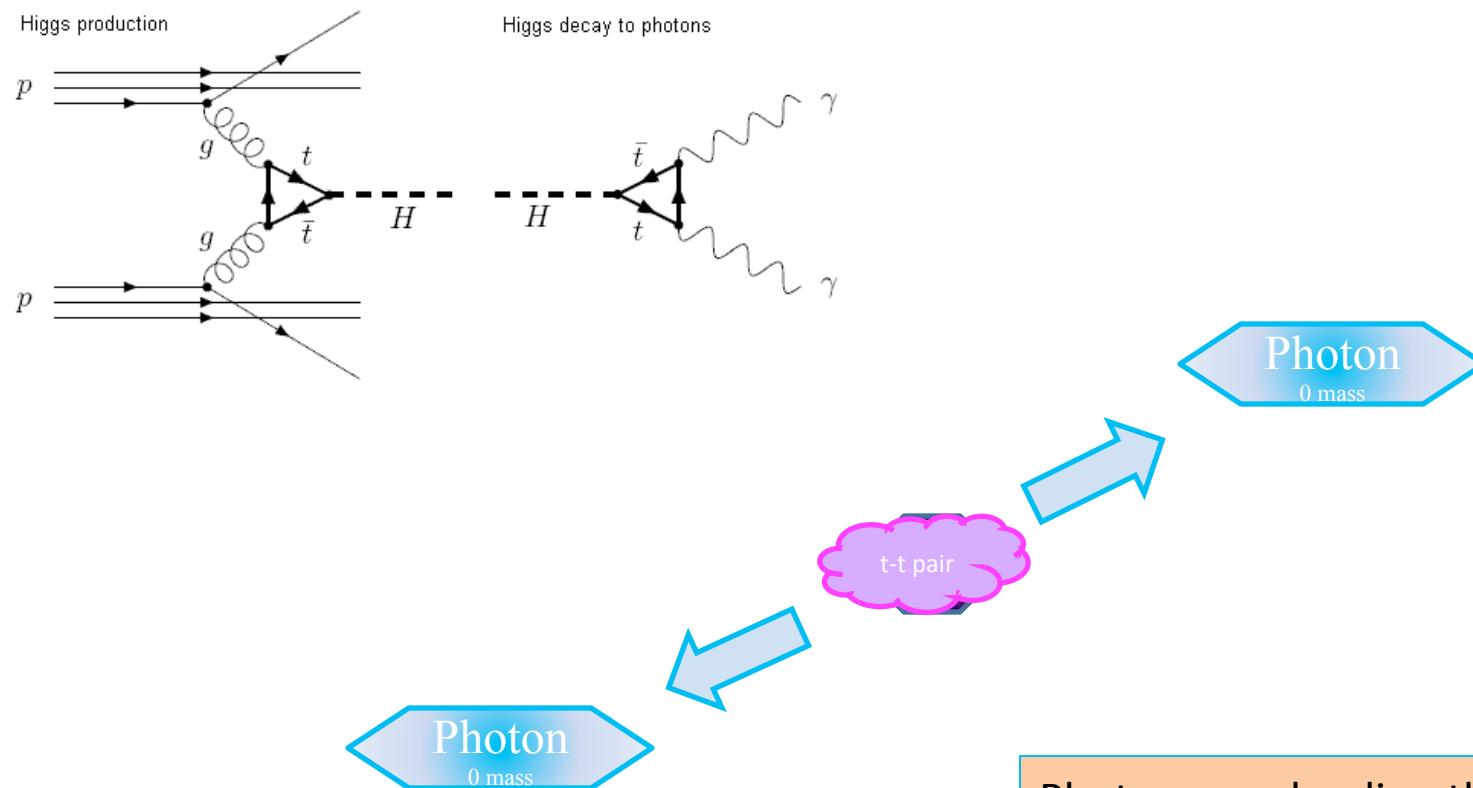


Gluons snap forming **quark – antiquark pairs**!

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

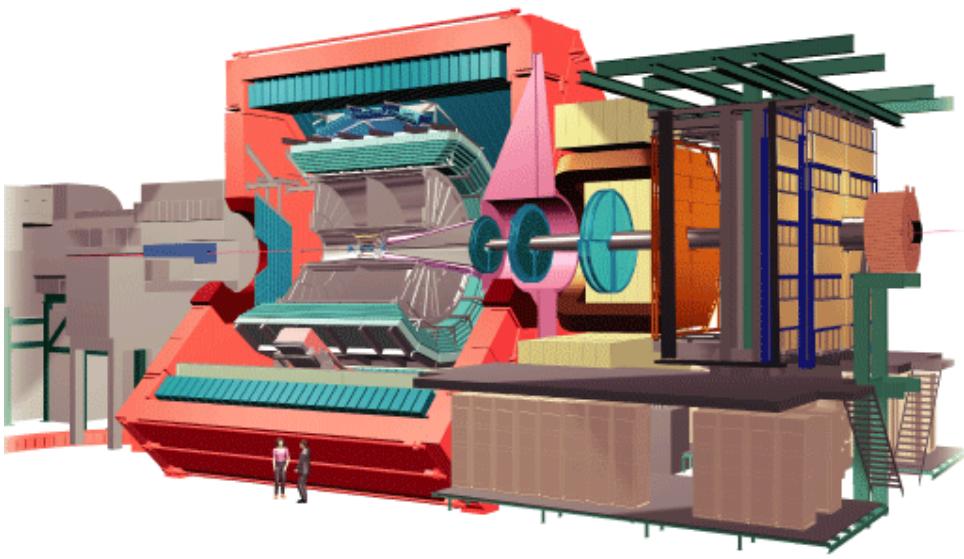
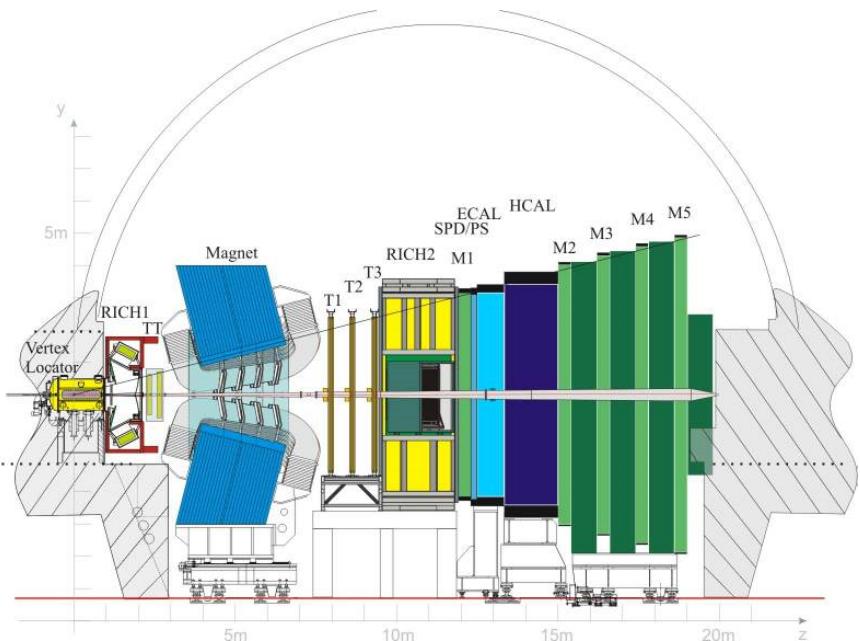
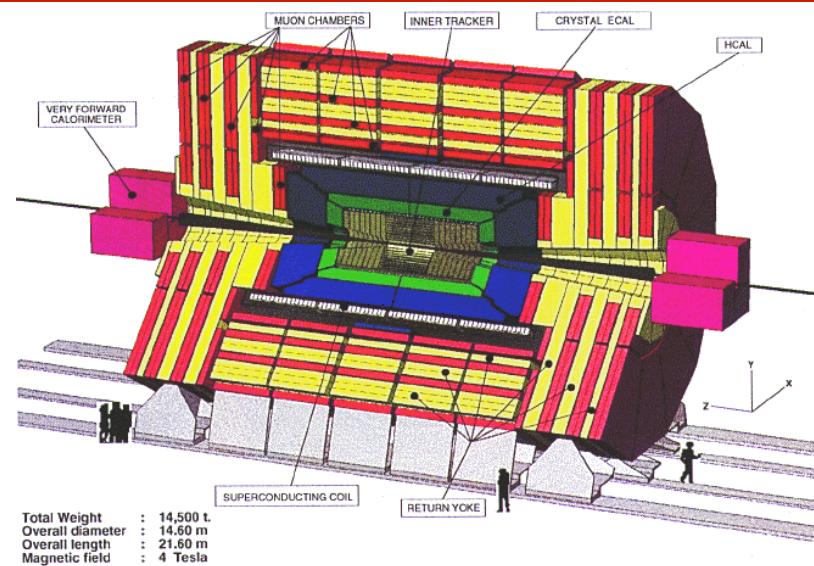
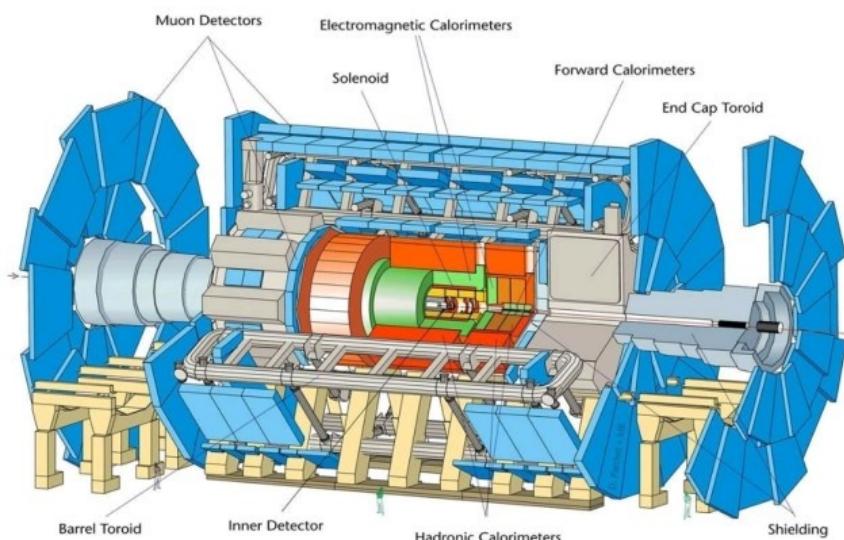
The stretched gluon snaps into a **top & antitop** quark pair of virtual particles!

The Higgs Boson Decays into Two Photons

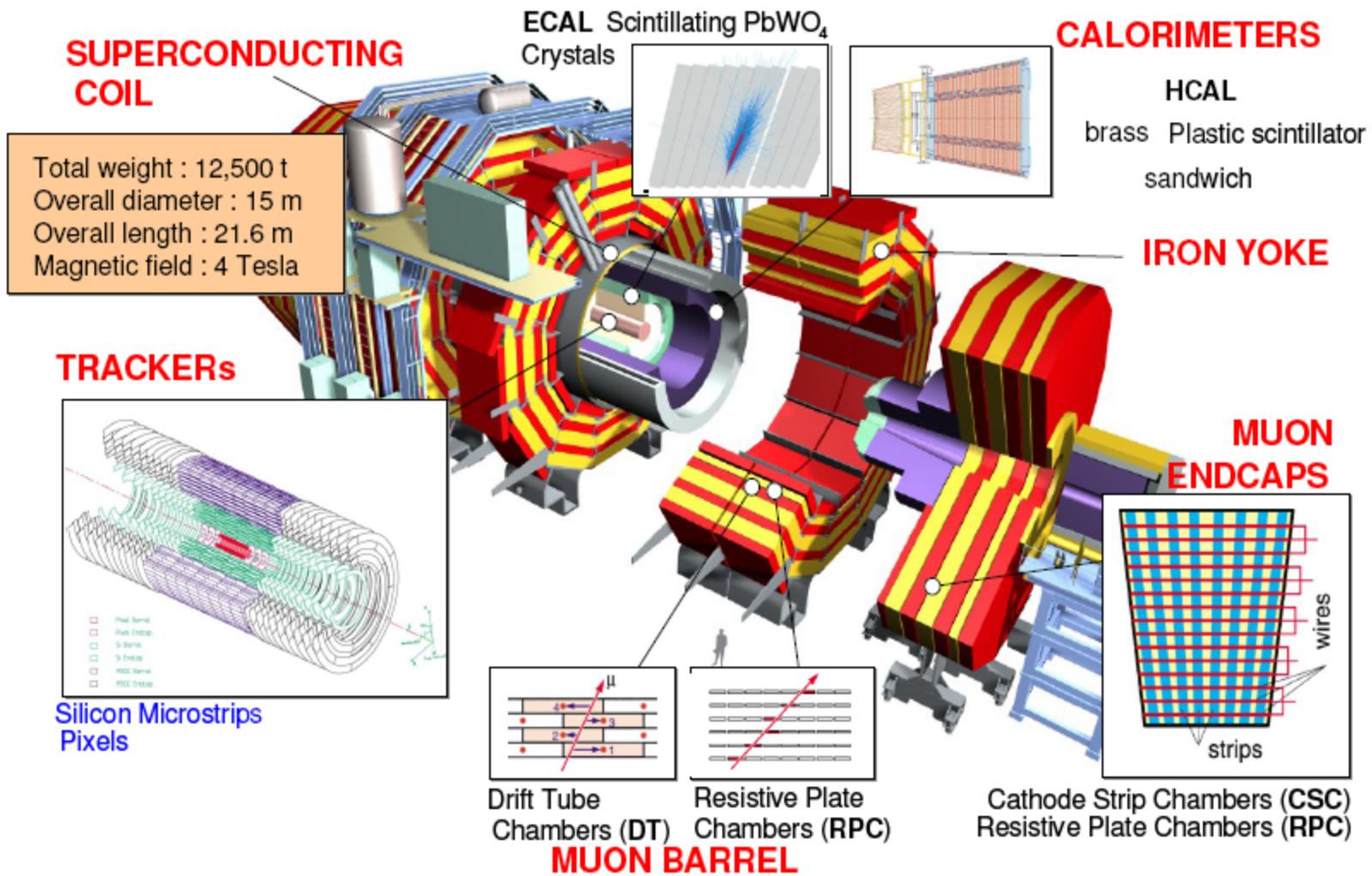


Photons can be directly observed with our detectors.

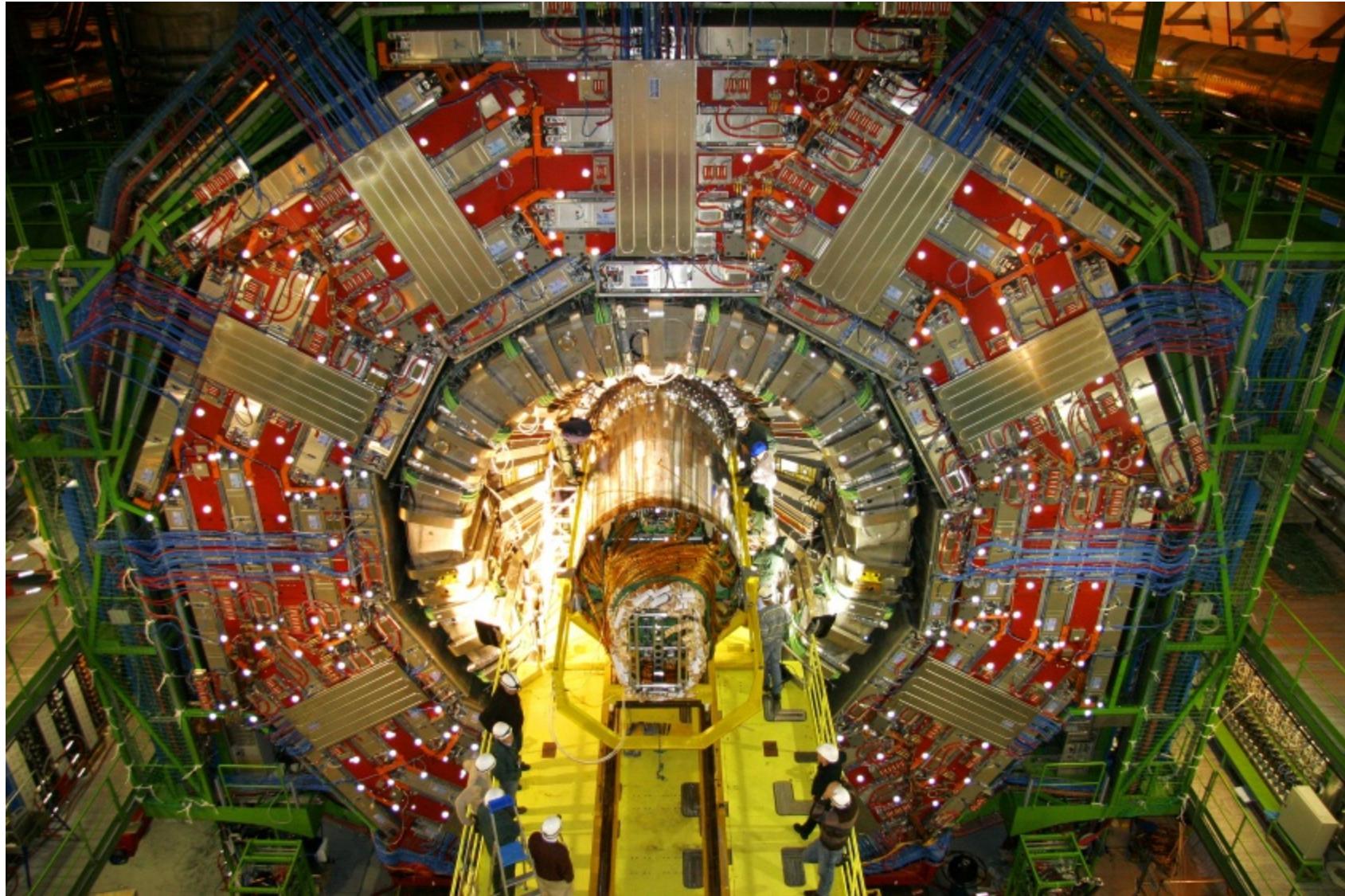
ATLAS, CMS, ALICE and LHCb



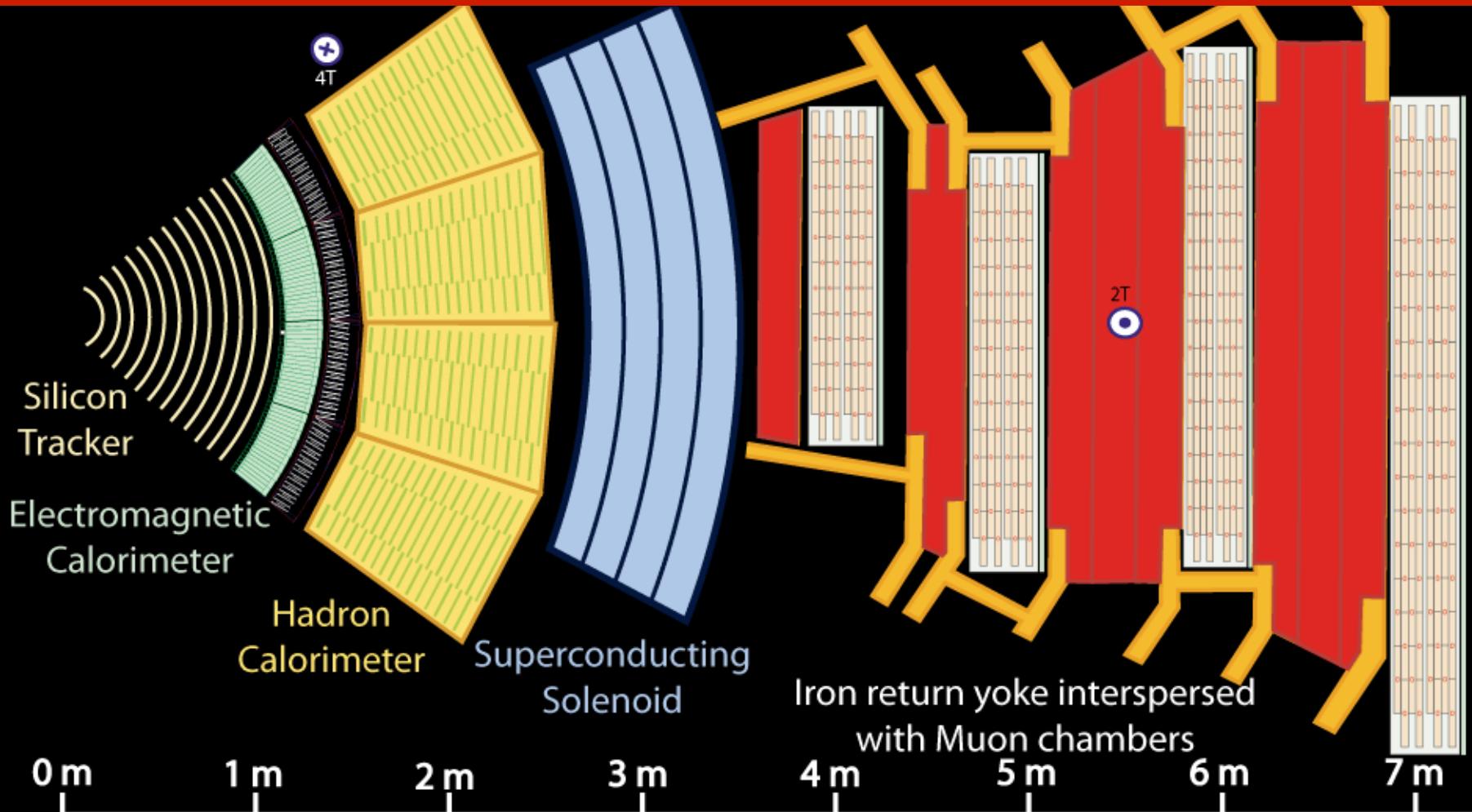
CMS



CMS



CMS



Key:

— Muon

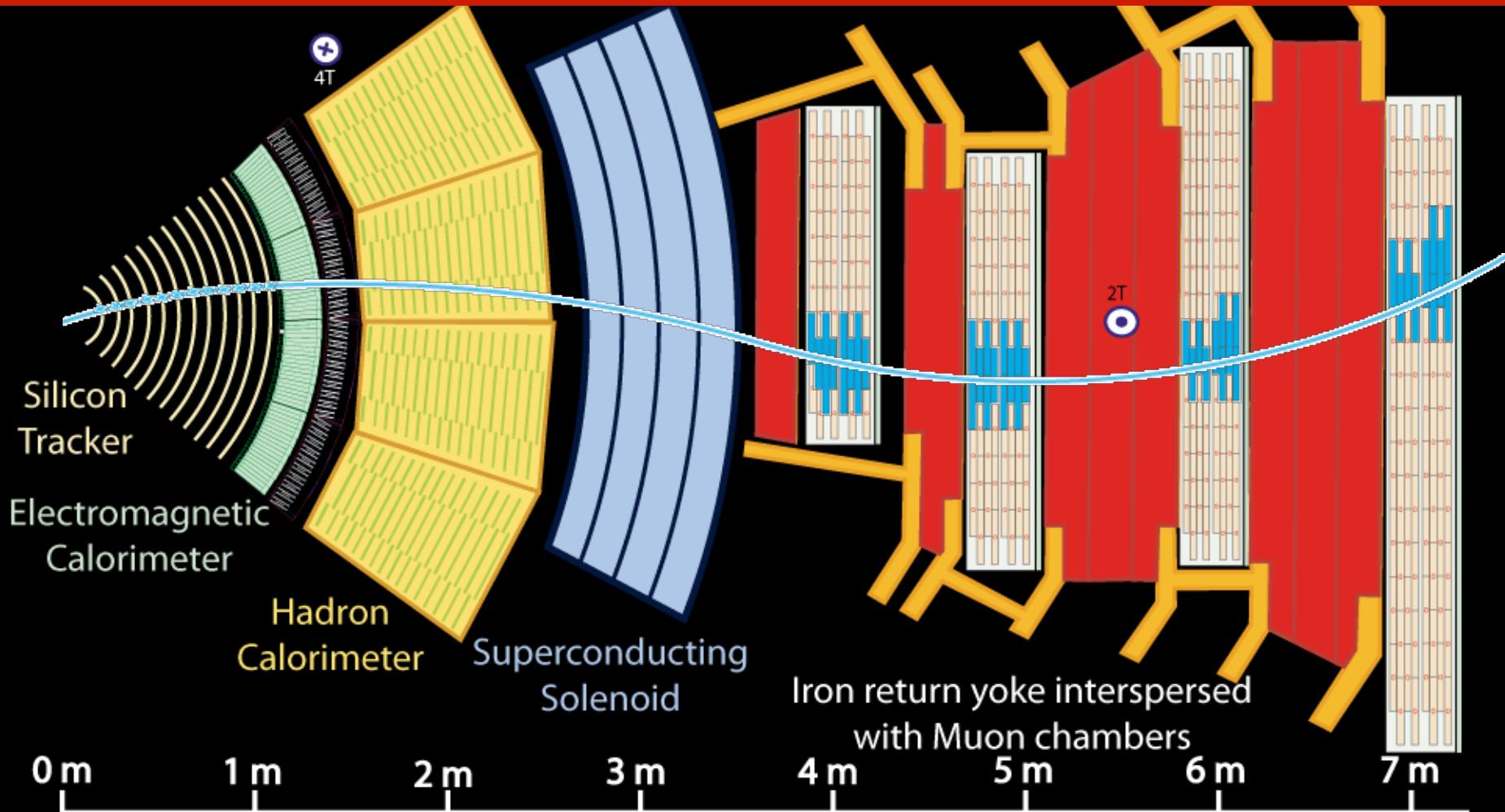
— Electron

— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

--- Photon

CMS



Key:

Muon

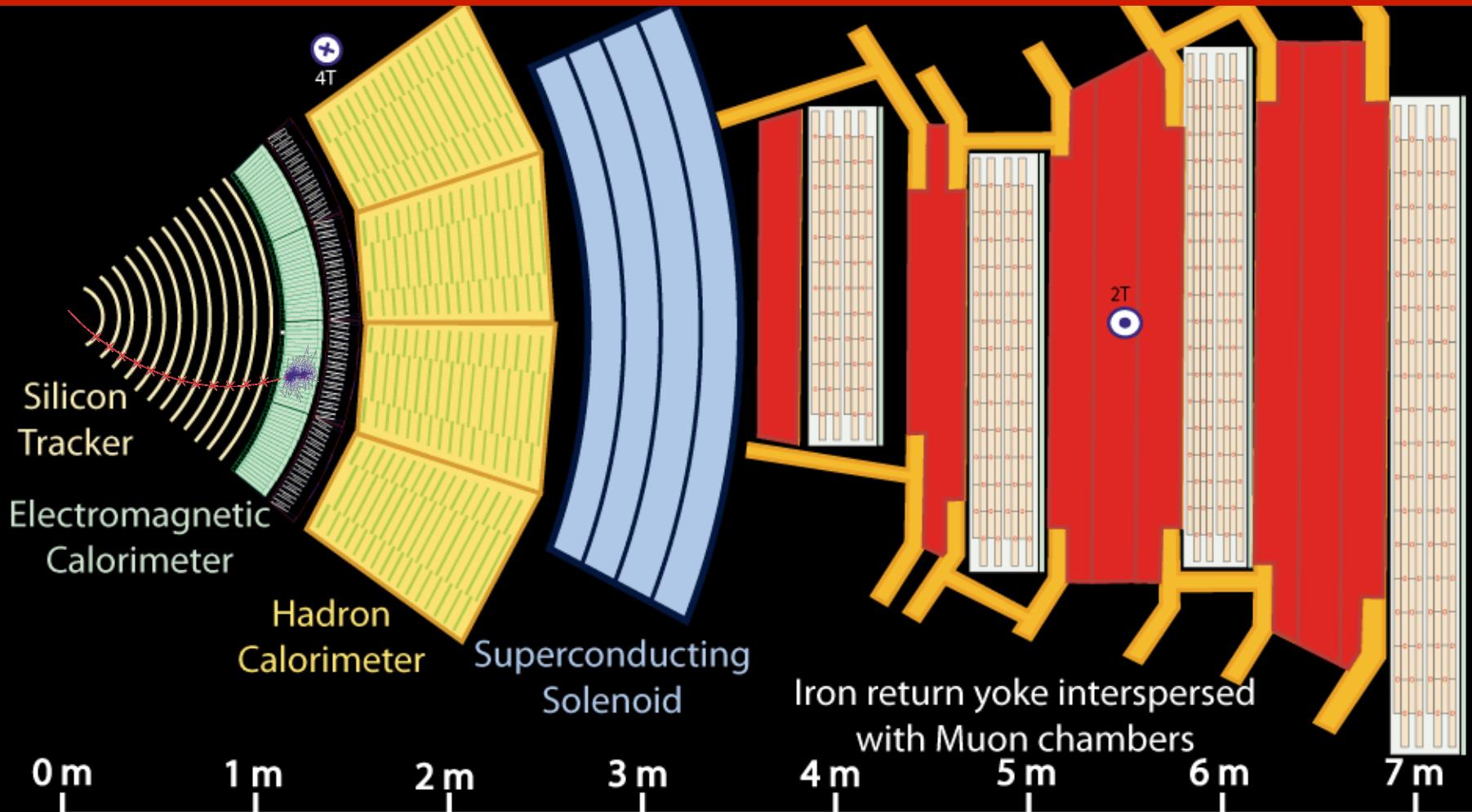
Electron

Charged Hadron (e.g. Pion)

Neutral Hadron (e.g. Neutron)

Photon

CMS



Key:

— Muon

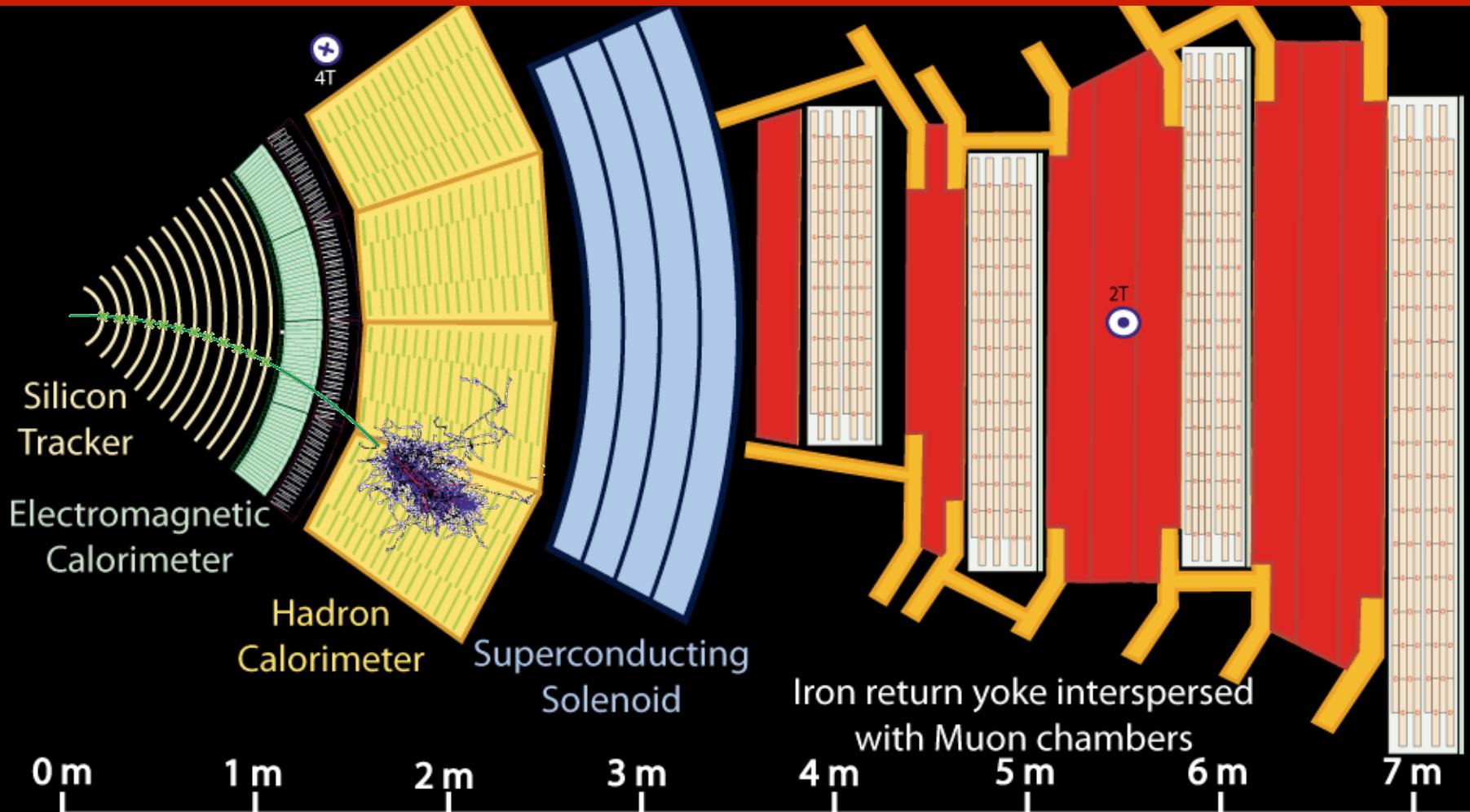
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CMS



Key:

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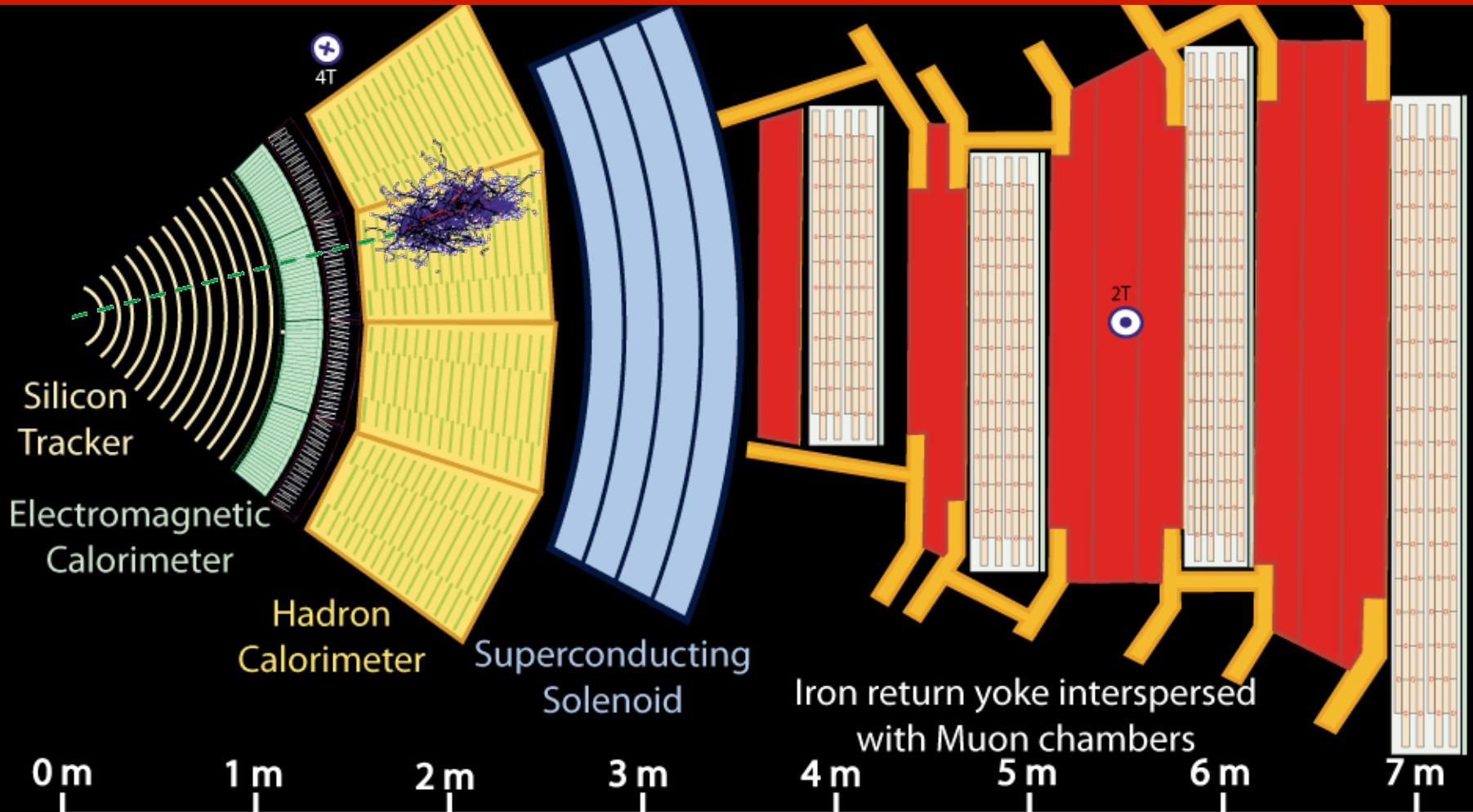
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CMS



Key:

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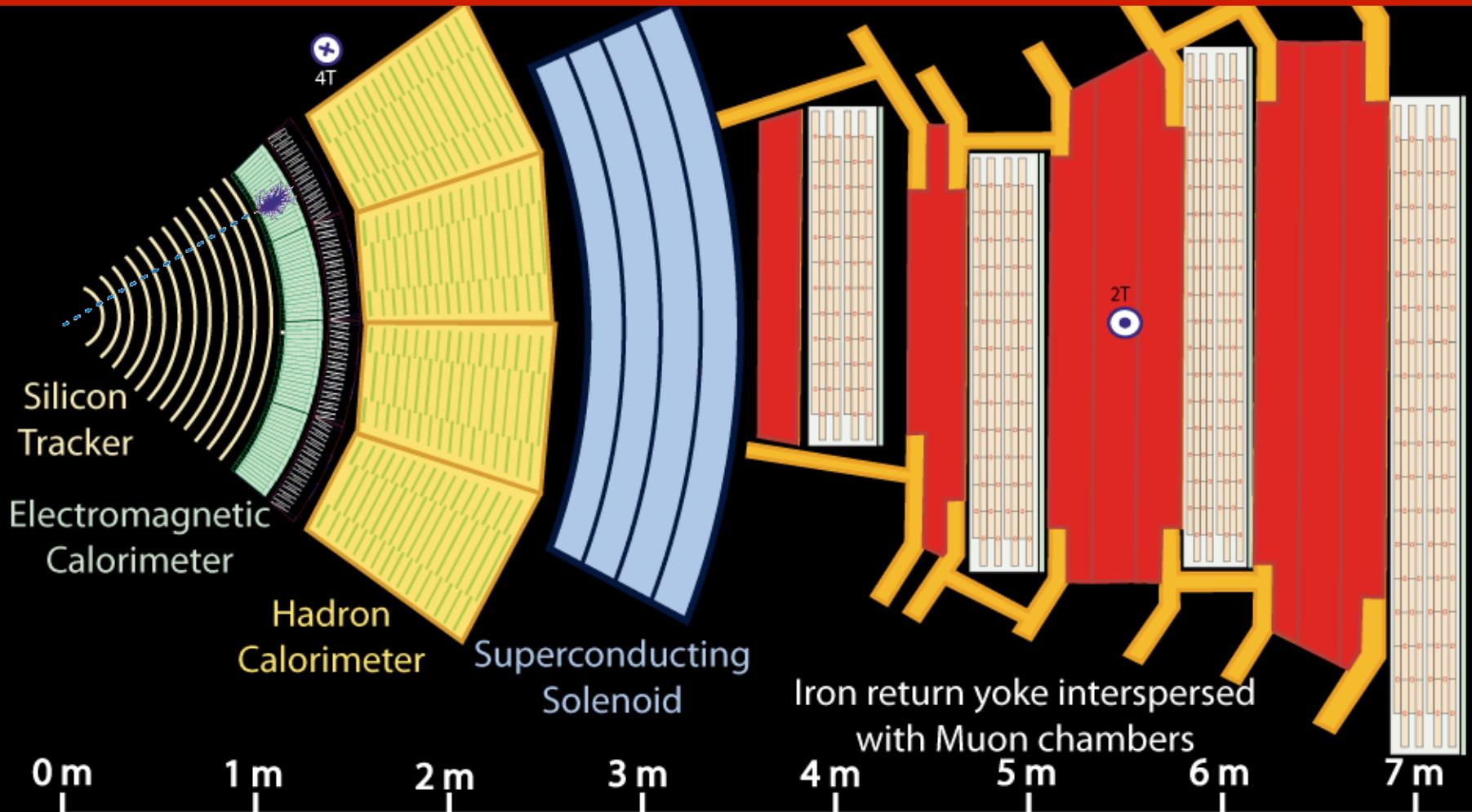
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— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

- - - Photon

CMS



Key:

— Muon

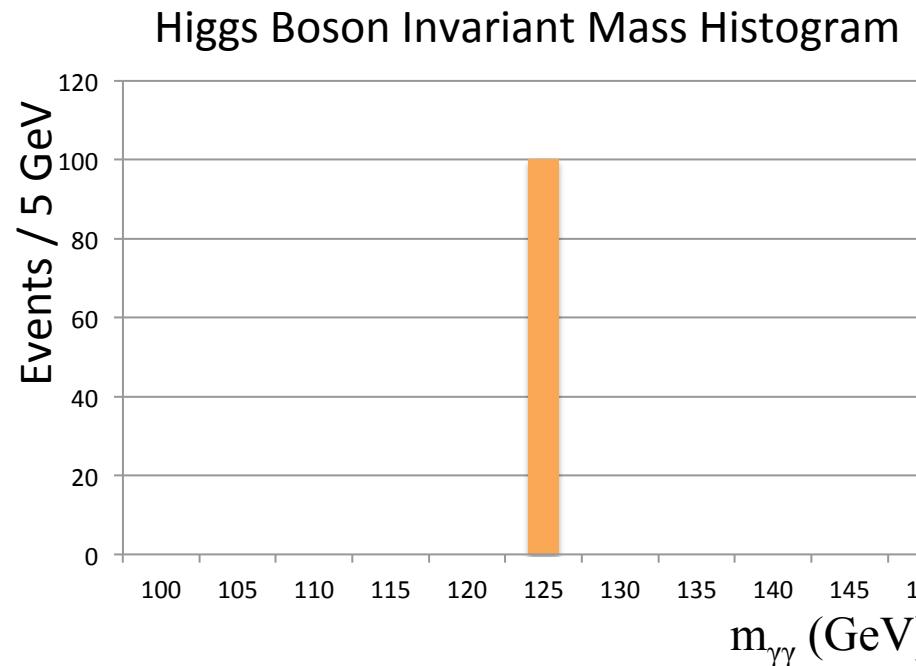
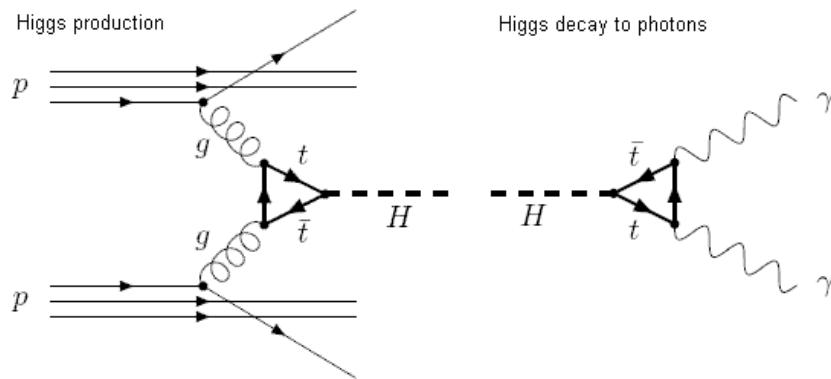
— Electron

— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

----- Photon

$H \rightarrow \gamma\gamma$ – Invariant Mass



Recall $E^2 = p^2c^2 + m^2c^4$ (Special Theory of Relativity)

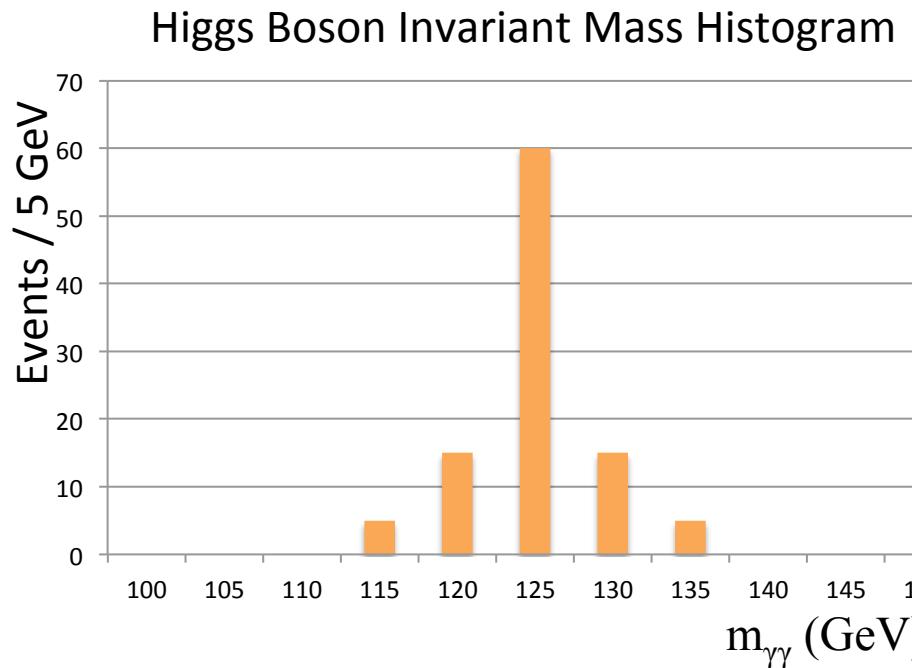
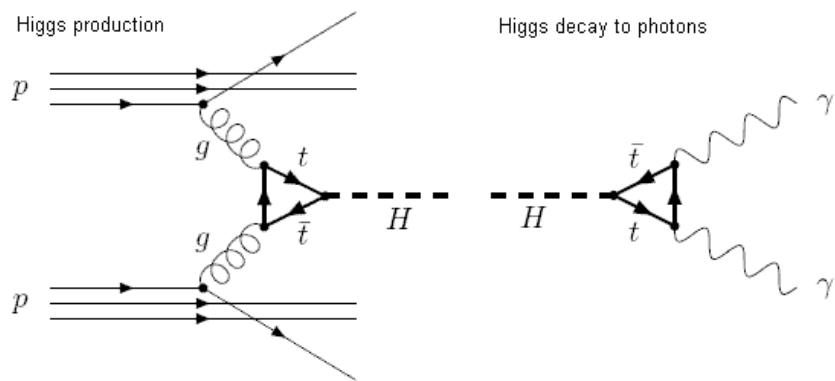
This holds true for the energy and momentum of the Higgs boson.

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.

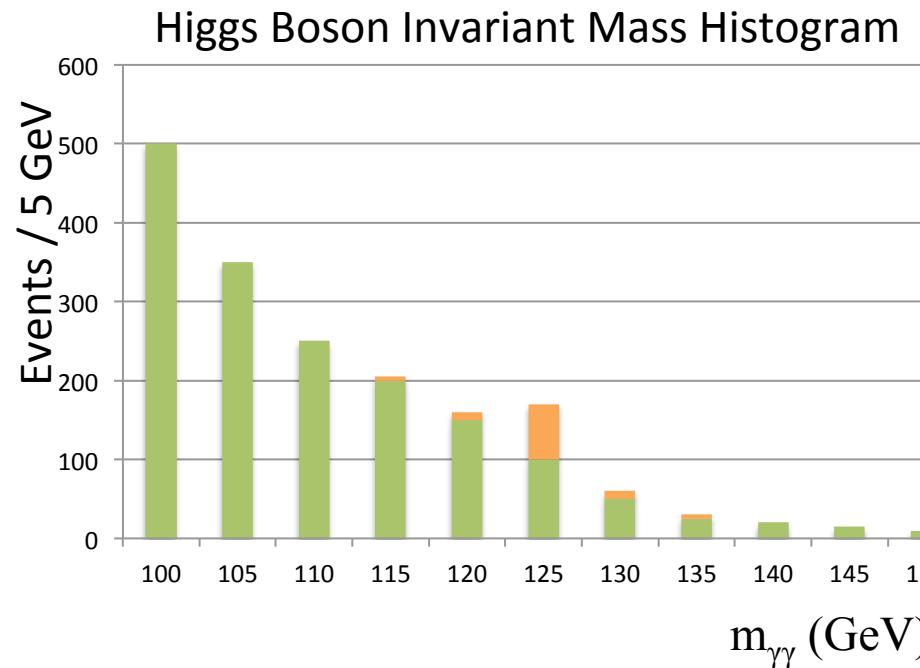
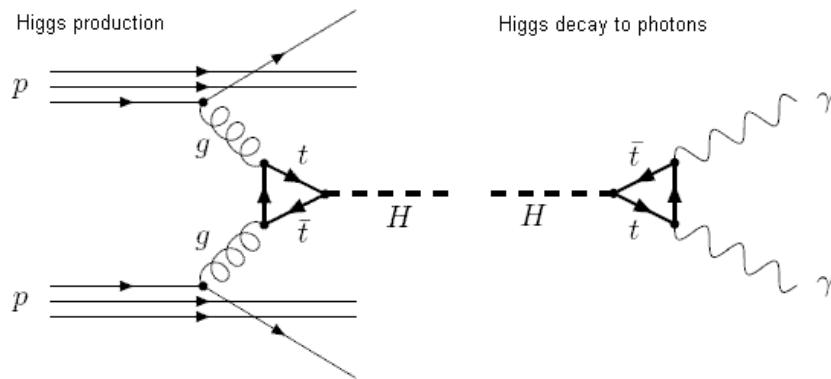
$\sqrt{E^2 - p^2c^2}$ will peak at the mass, mc^2 , of the Higgs boson.

$H \rightarrow \gamma\gamma$ – Invariant Mass



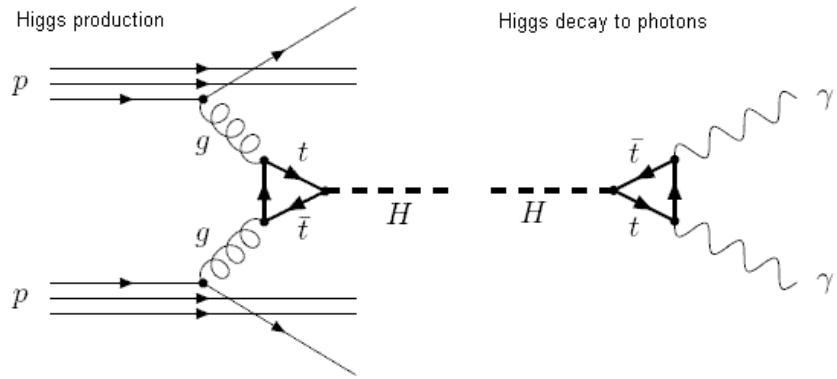
But, this is not a perfect detector. So there will be tails. The width of this distribution is the detector resolution.

$H \rightarrow \gamma\gamma$ – Invariant Mass

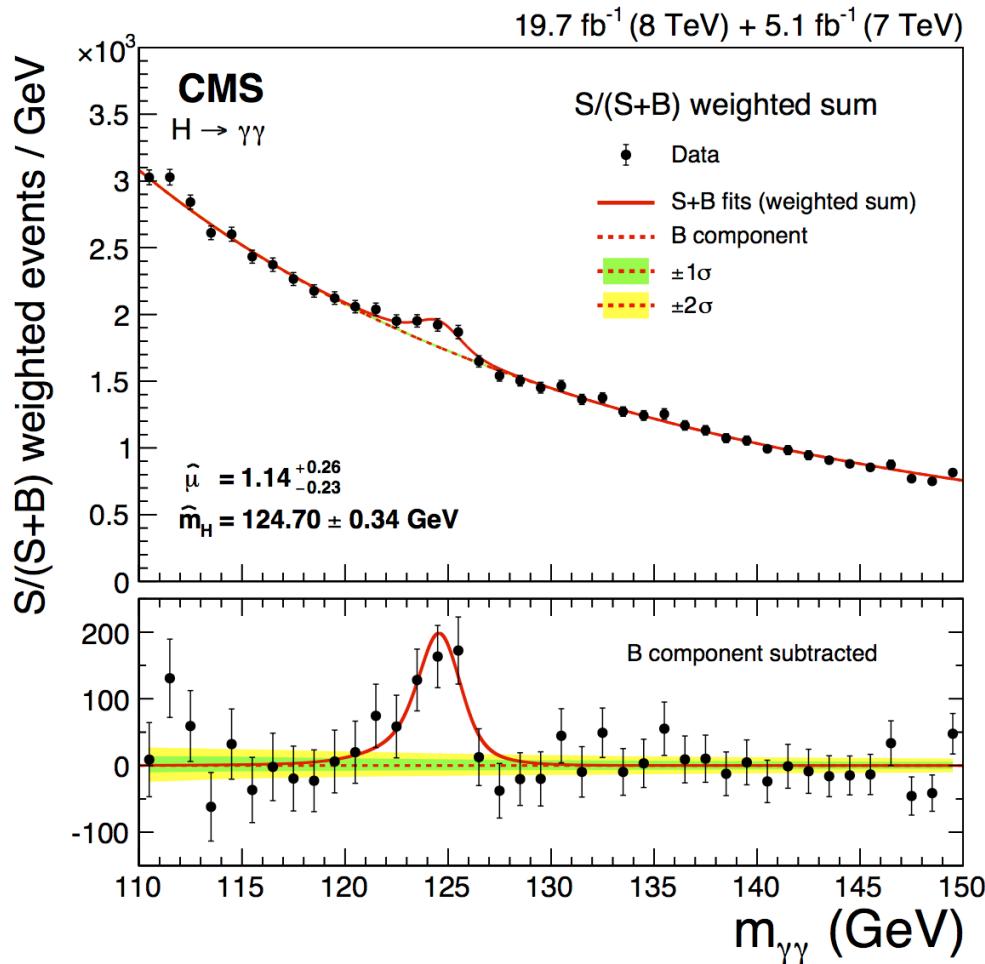


- A cornucopia of processes also produce pairs of photons in proton-proton collisions. The invariant mass for these will not peak at the Higgs mass. These are background processes
- We distinguish the peaking signal sitting on top of the background using powerful statistical methods

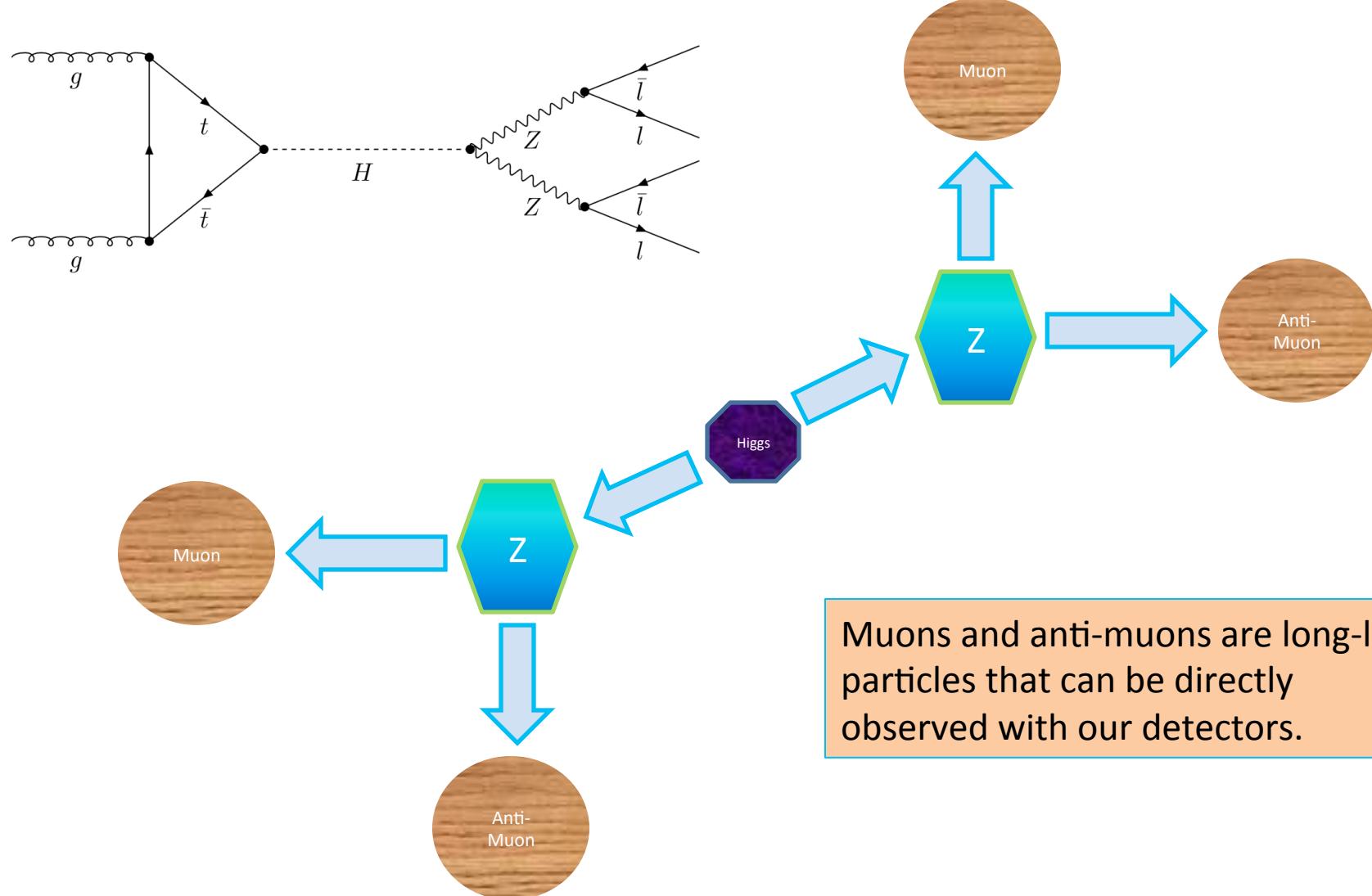
$H \rightarrow \gamma\gamma$ – Invariant Mass



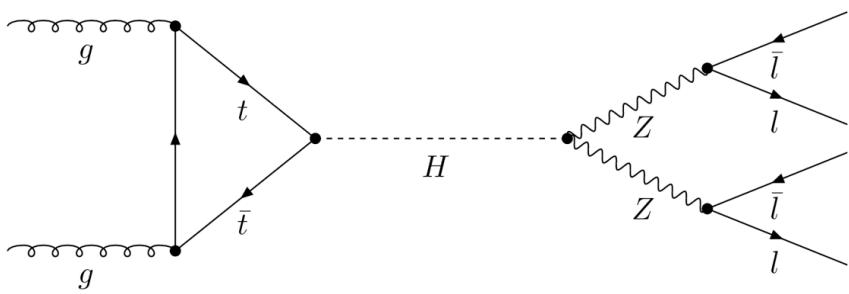
- The probability that the peak arises from statistical fluctuation is less than **1 in 3 million** (5 sigma)
- This is a sound observation



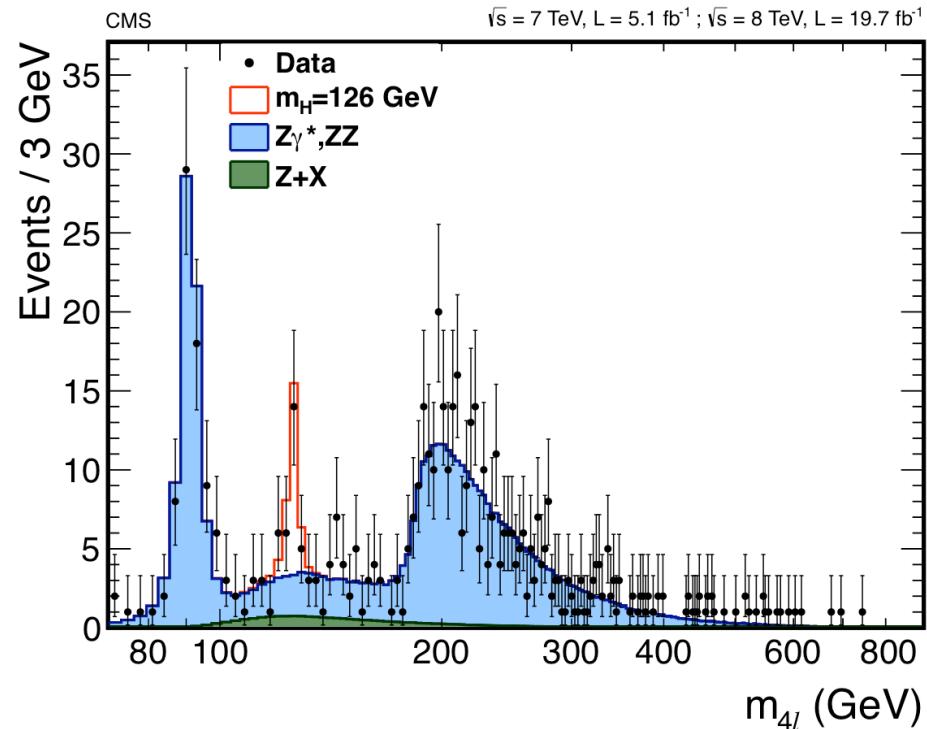
The Higgs Boson Decays into Muons



$H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$ – Invariant Mass



- The probability that the peak arises from statistical fluctuation is less than **1 in 500 billion** (6.8 sigma)
- **Observation** if there ever was one!
- The Higgs couples to both matter particles and force carriers



The Higgs boson has been observed

Discovery of the Higgs Boson



"I think we got it"
Rolf Heuer,
4th of July, 2012

Several properties were tested over the next 2 years. The particle is entirely consistent with the Higgs boson

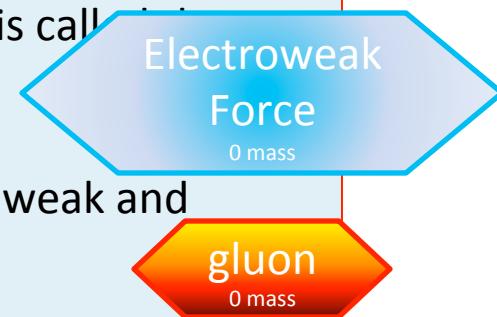


© ITV

Outstanding Mysteries – Unification of the Forces

Grand Unification and Supersymmetry

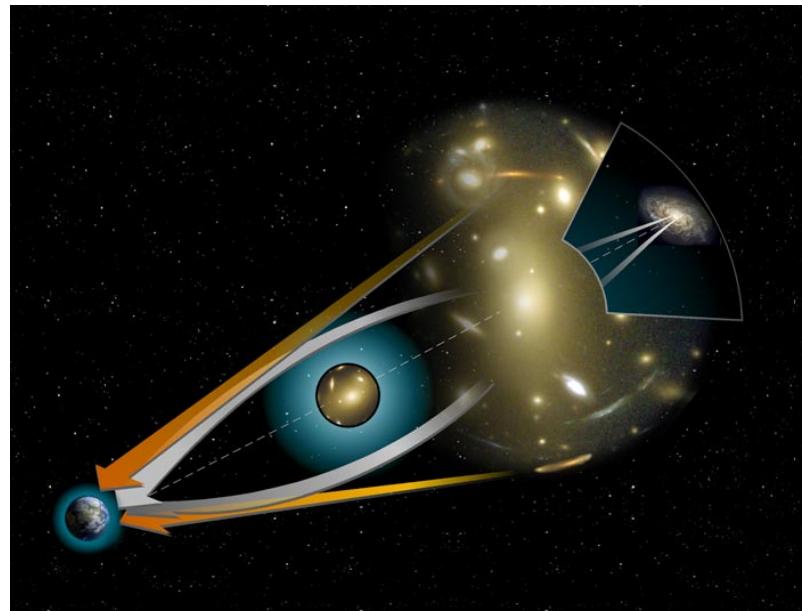
- Every matter particle follows Fermi-Dirac statistics. Every force carrier particle follows Bose-Einstein statistics. There is theoretical reason to believe that every matter particle has a “supersymmetric” twin with identical charge properties but following Bose-Einstein statistics. And every force carrier particle has a “supersymmetric” twin with identical force carrying properties but following Fermi-Dirac statistics. This is called the theory of *Supersymmetry*.
- *Supersymmetry* offers a compelling way to unify the Electroweak and Strong forces.
- *Supersymmetry* can also offer explanations of the *Higgs* 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.



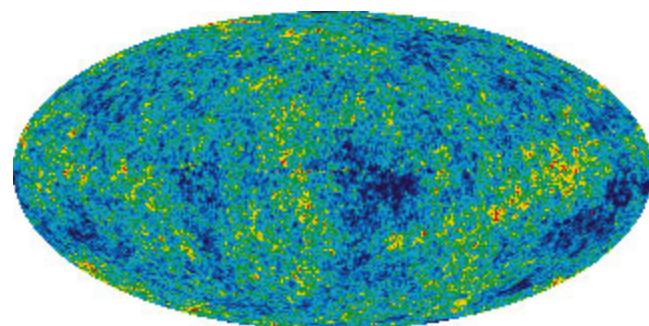
Gravitational lensing

What is dark matter composed of?

- *Supersymmetric* particles perhaps? The lightest supersymmetric particle predicted by theory 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.

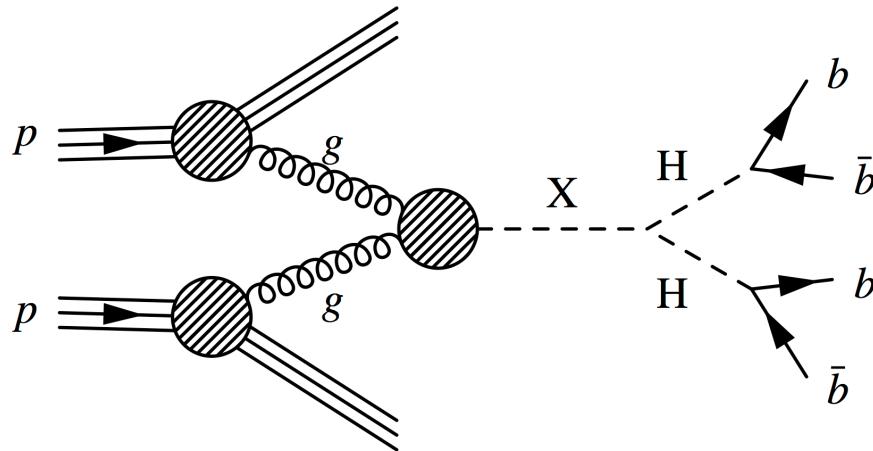
But if we did have equal amounts of matter and antimatter, they would have annihilated each other out eventually.

We are still here and no naturally occurring antimatter is in sight! We've looked as near and as far into the universe as we could and there is no evidence for antimatter agglomerations.

For every billion particle-antiparticle pairs produced during baryogenesis (10^{-6} seconds after the Big Bang), there seems to have been an excess of one particle. Everything we see in the universe today is that excess.

Some laws of nature may not be impartial towards matter and antimatter. (*Charge-Parity Violation*)

Using the Higgs to Search for New Physics



Any narrow-width resonance, X , decaying to pairs of Standard Model Higgs bosons, decaying to 4 b-jets

- The **Higgs boson is now a tool** for searches Beyond the Standard Model. Experimentally feasible and important to search for HH resonances.
- For example, searches for HH resonances can rule out some models of Warped Extra Dimensions

Conclusions

The Higgs boson exists. Humanity has seen it. The electromagnetic and weak nuclear forces are one force split asunder by the Higgs field.

The mass of the Higgs at 125 GeV is a balancing act. Calls for explanation in terms of Supersymmetry at the TeV scale.

The Higgs is now a tool to search for new physics

Outstanding mysteries remain in Dark Matter, Dark Energy and the matter anti-matter asymmetry.

The world is staggeringly more complex and awe-inspiring than pre-medieval fairytales that attempt to explain it. There is no reason to hide behind their easy, but wrong, answers any more.

Backup Slides



Norse Creation Story: When the cold of Niflheim touched the fires of Muspell, the giant Ymir and a behemoth 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.



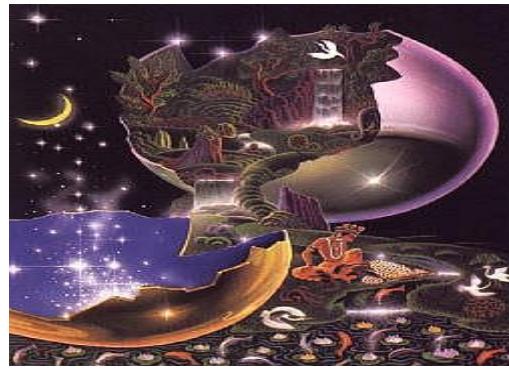
In the Beginning...



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

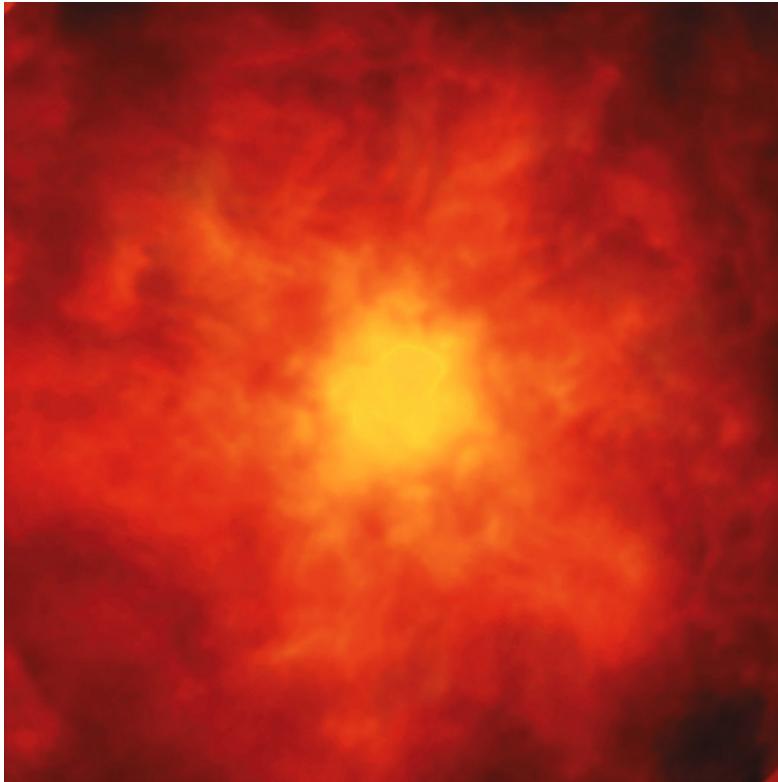
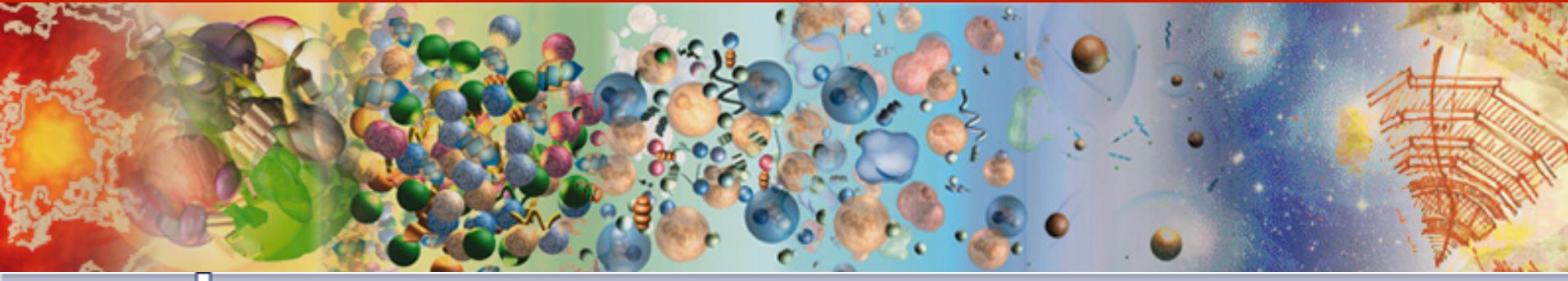


A Chinese Creation Story: Phan Ku hatched from an egg and grew for 18,000 years, pushing his shell apart into heaven and earth. Then he died and his remains became the sun and the moon. Humans are parasites on his body.



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

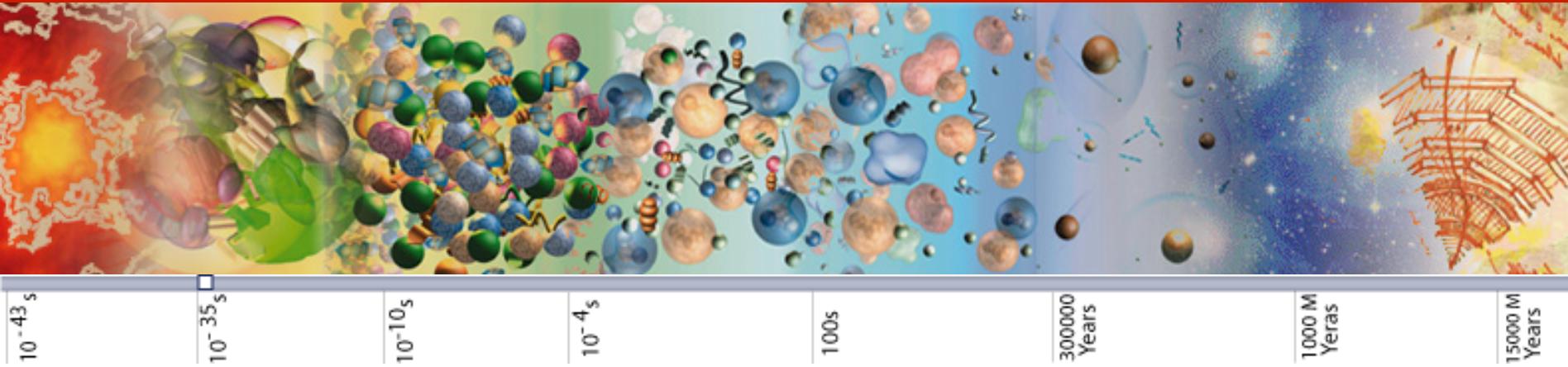
There was a Bang



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 ($10^{-35} \text{ sec}, 10^{27} \text{ K}$)

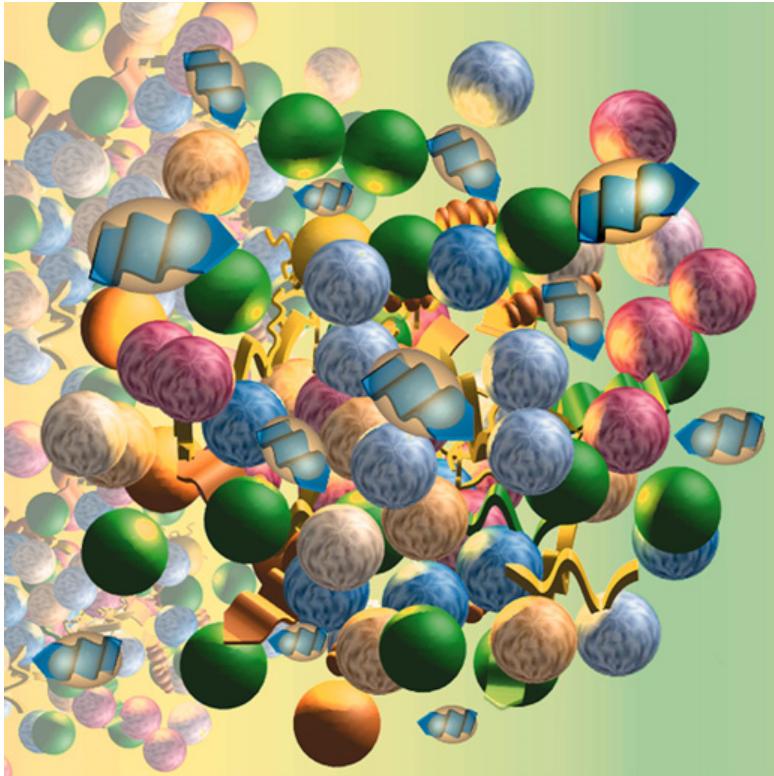
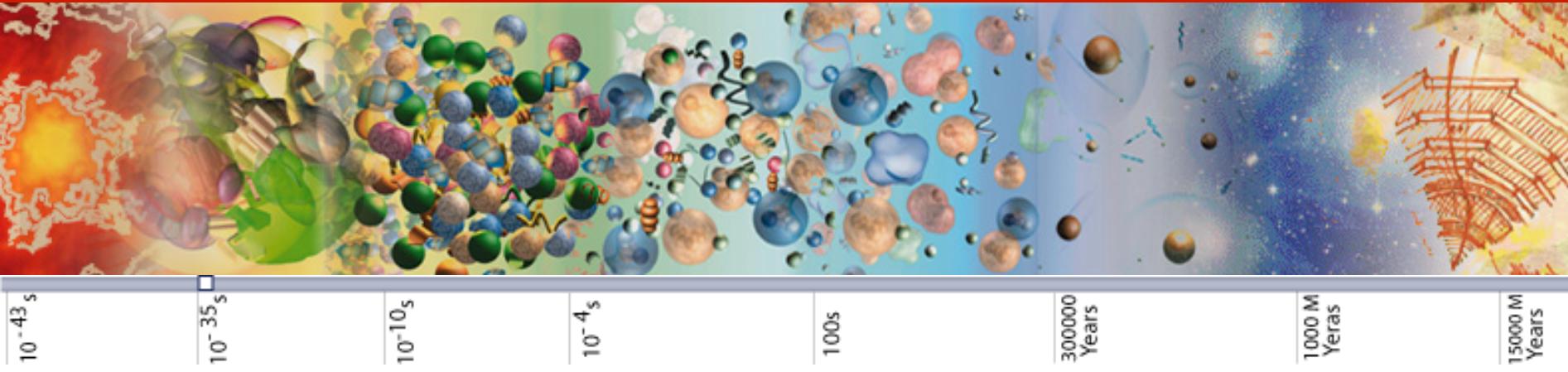
- The universe *inflates* by a factor of 10^{50} in ~ 100 seconds. It reaches a total size of 10^{23} m .

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

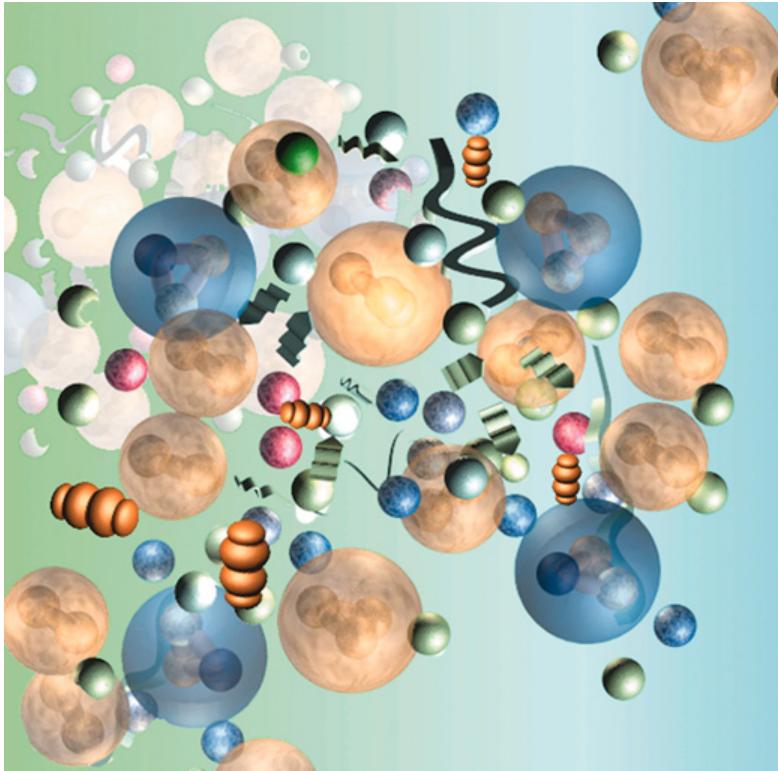
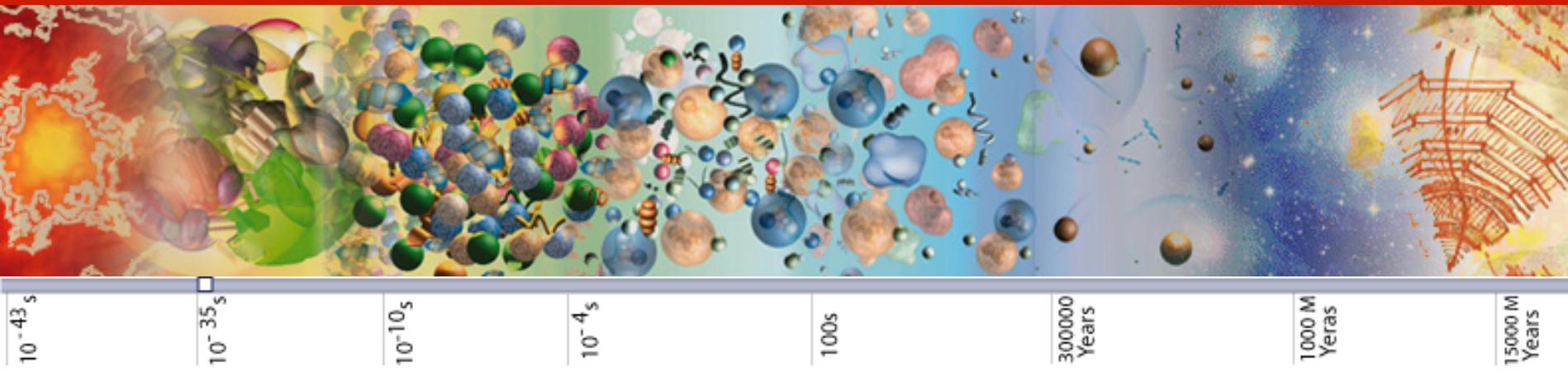


Electroweak Degeneration Era (10^{-10} sec, 10^{15} K)

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



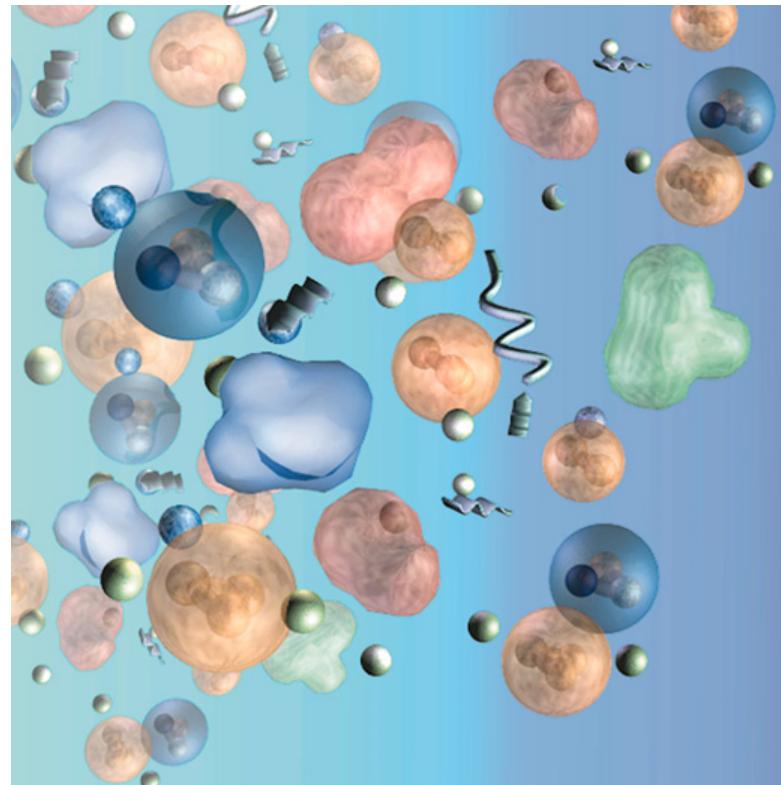
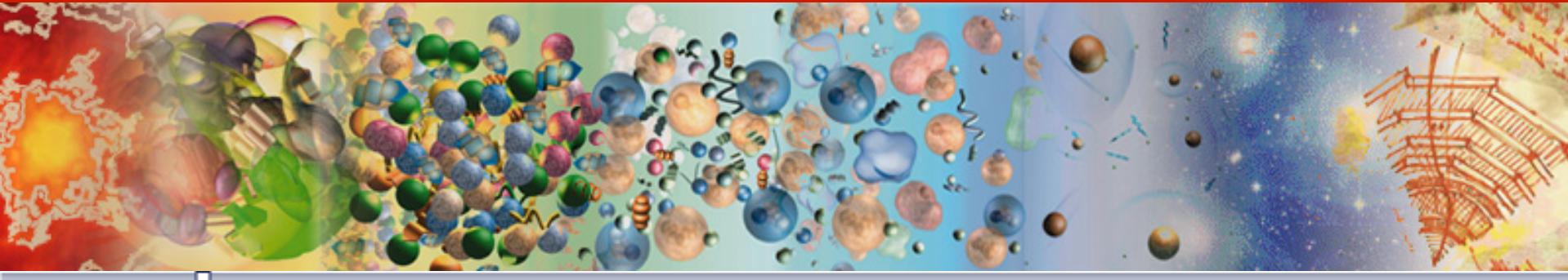
Protons and Neutrons form (10^{-4} sec, 10^{13} K)

- 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

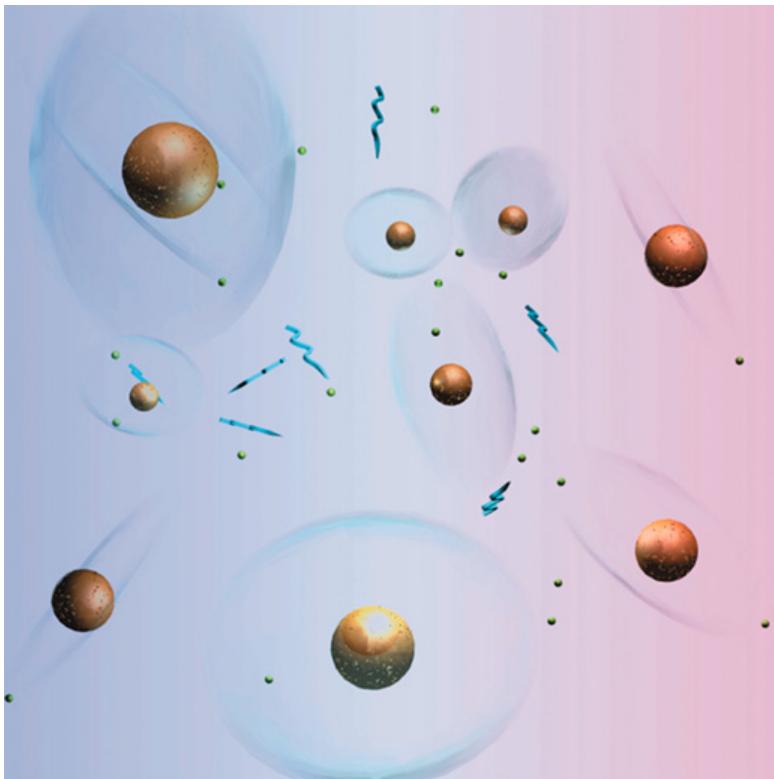
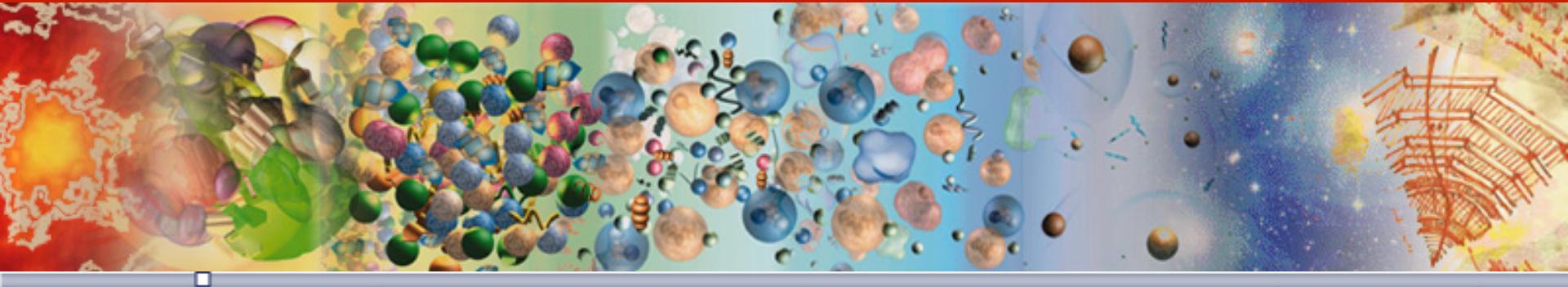
Atomic Nuclei formed



Helium Age ($100 \text{ sec}, 10^9 \text{ K}$)

- Helium nuclei can form now. Conditions similar to stars or hydrogen bombs.
- Atoms cannot form as yet.

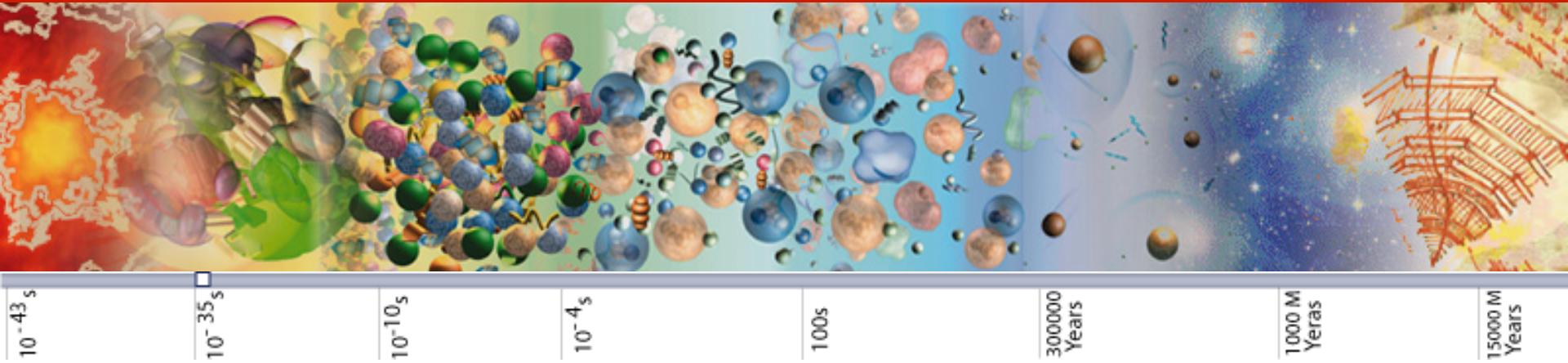
Atoms formed and Light could travel freely



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!

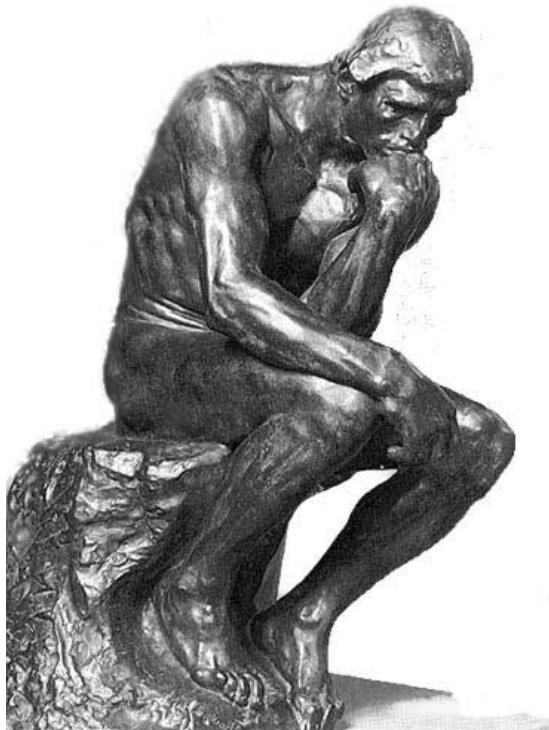
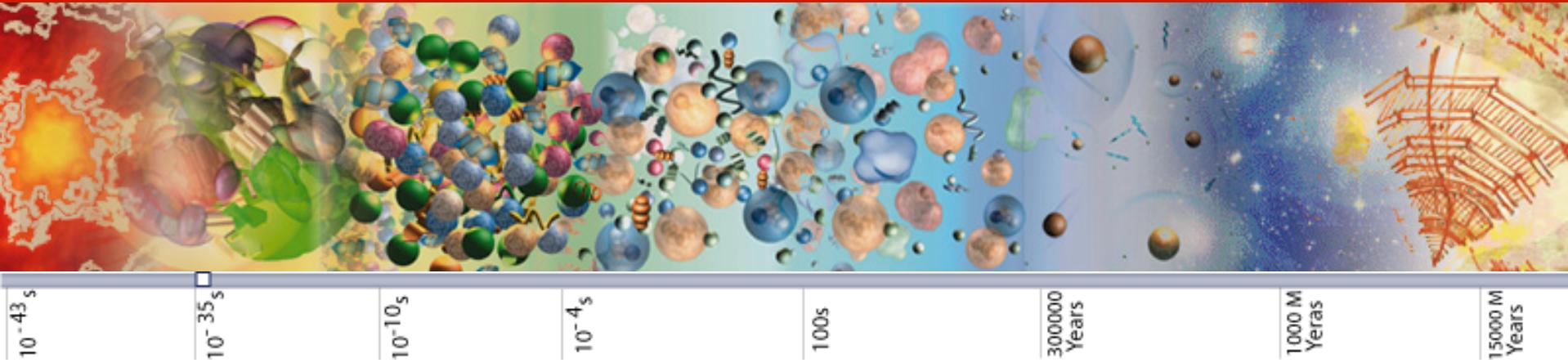
Stars and Galaxies formed



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

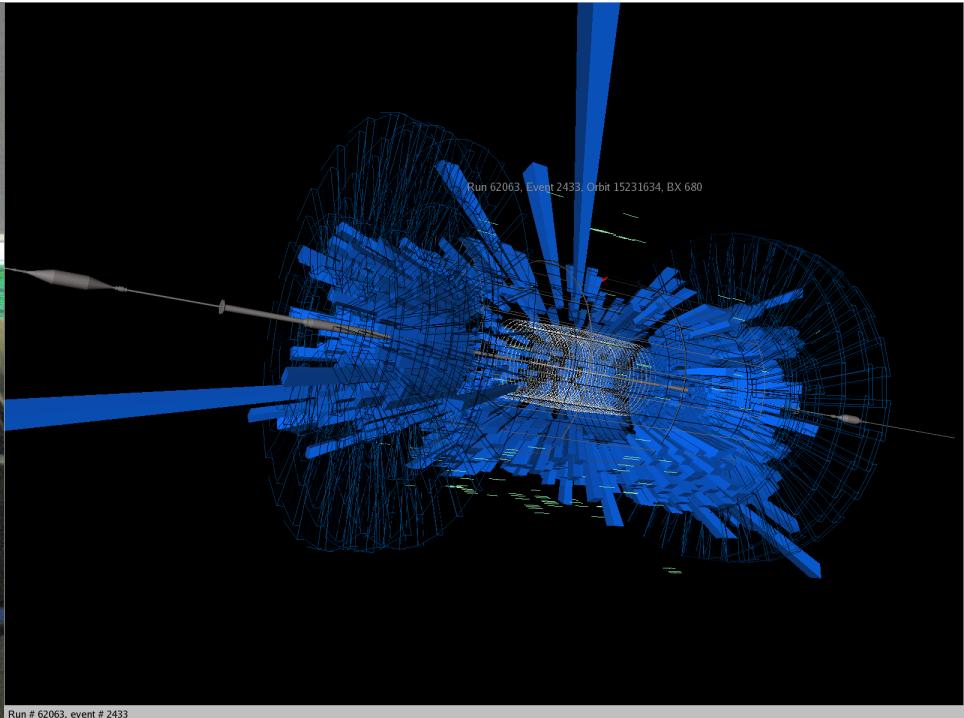
Life has arisen to soak in the Mystery



Today (13.7 billion years, 3 K)

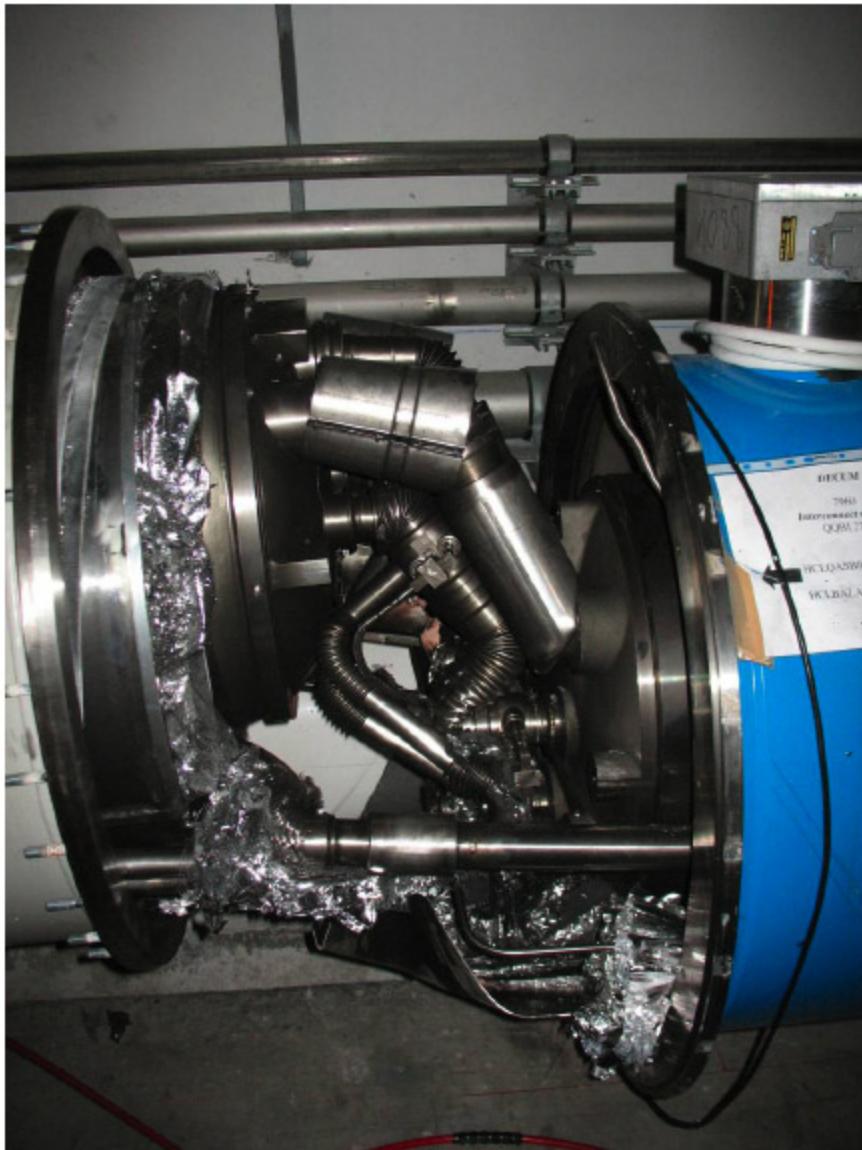
- The dust of stars spewed out in supernovae explosions accumulate into planets
- Carbon atoms concatenate into complex molecules while the relentless energy from stars animate their ever-more-sophisticated dance of self-replication.
- And out of the stardust living creatures emerge to observe the universe and ponder its mystery

Beam through CMS (10th September 2008)





19th September Malfunction

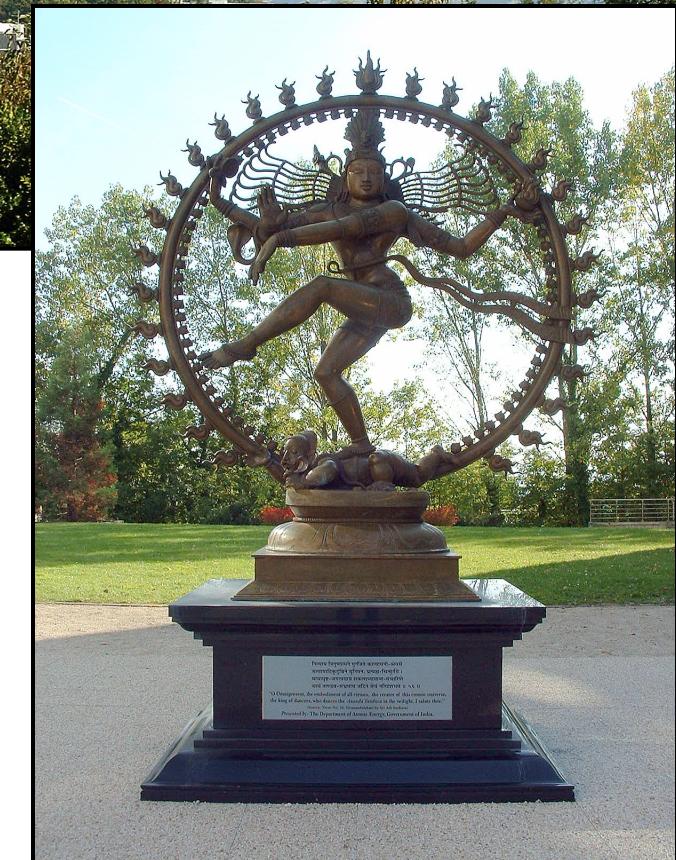
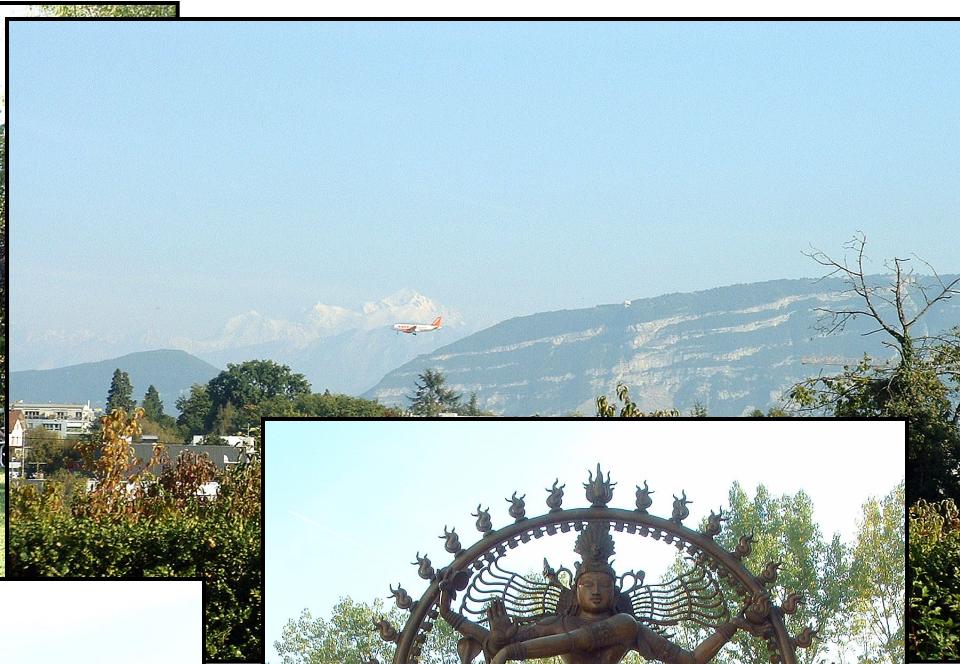


Repairs under way to be ready for physics by the *summer of 2009*

Life at CERN

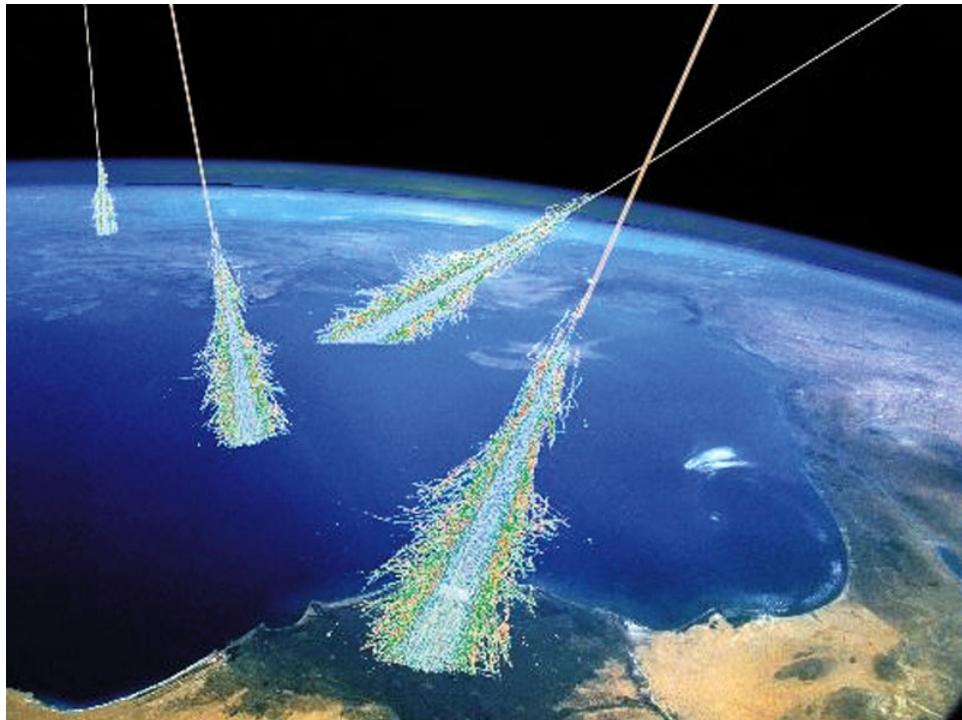


Life at CERN



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.

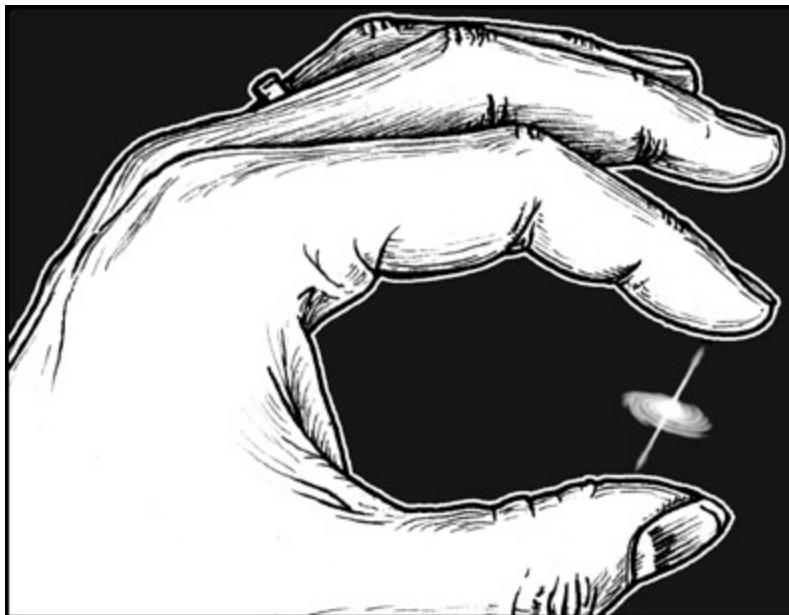
Cosmic rays from outer space routinely bombard the earth and its atmosphere with up to 10^{20} eV.

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



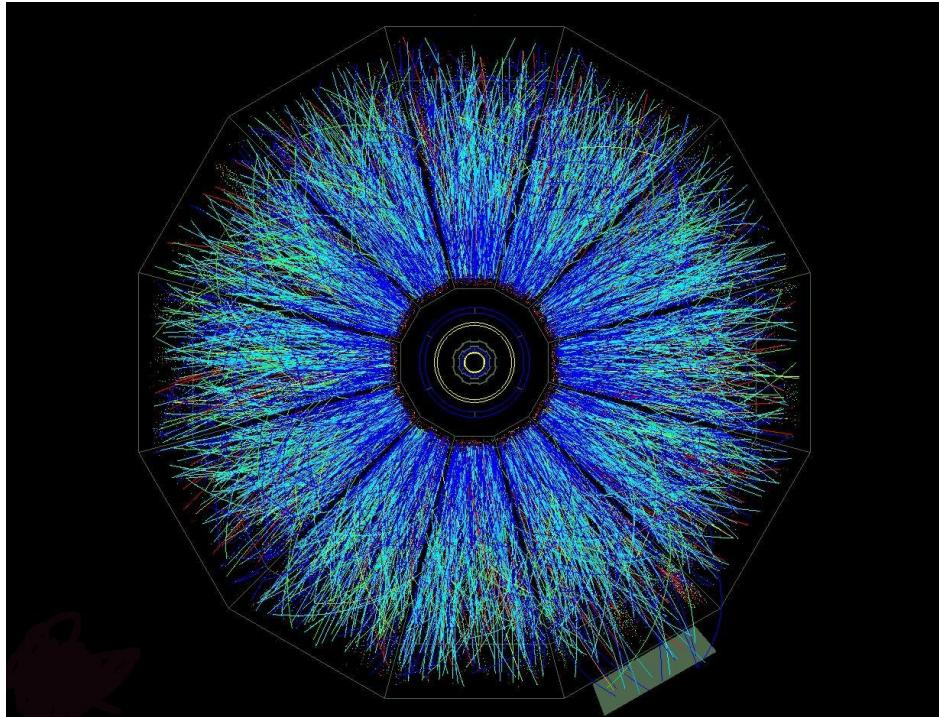
Some speculative theories predict the formation of microscopic black holes at the LHC.

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

No time to accrete matter.

Is this Dangerous?

Strangelets

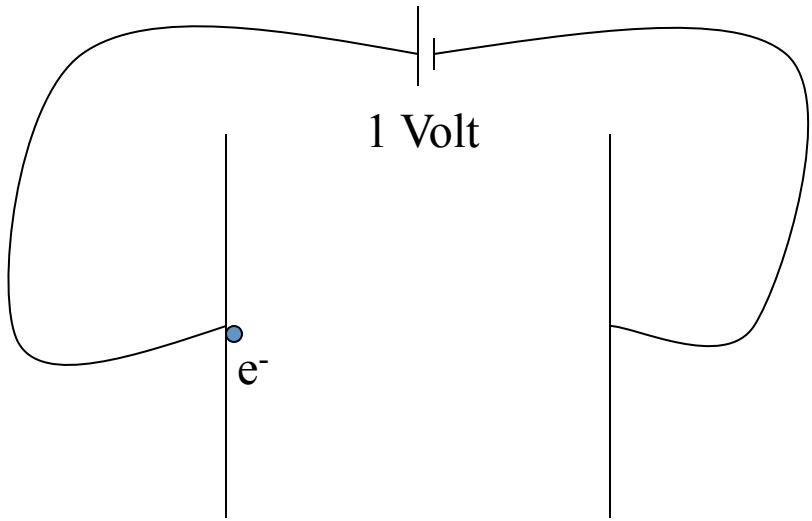


Strangelets are highly speculative conglomerations of equal amounts of up, down and strange quarks which may be stable.

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

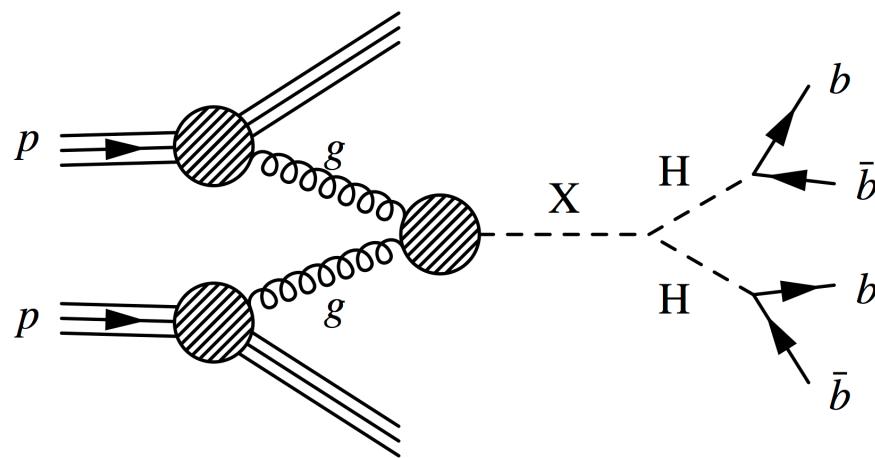
$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

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).

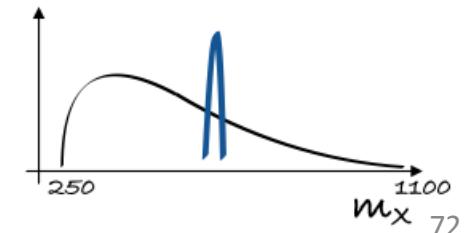
$$\text{mass of a proton} = 1.67 \times 10^{-27} \text{ kg} = 938 \text{ MeV}/c^2 \approx 1 \text{ GeV}$$

What are we searching for?



Any narrow-width resonance, X , decaying to pairs of Standard Model Higgs bosons, decaying to 4 b-jets

- The **Higgs boson is now a tool** for searches Beyond the Standard Model. No resonant HH production in SM. Negligible non-resonant HH production. Experimentally feasible and important to search for HH resonances.
- Highest Higgs branching fraction to bb . Unearth signal from under **copious 4-jet QCD background**. We rely on:
 - Our most **powerful b-tagging** algorithm
 - **Data-driven modeling** of the QCD multi-jet background
 - Good **$m(bb)$ resolution**



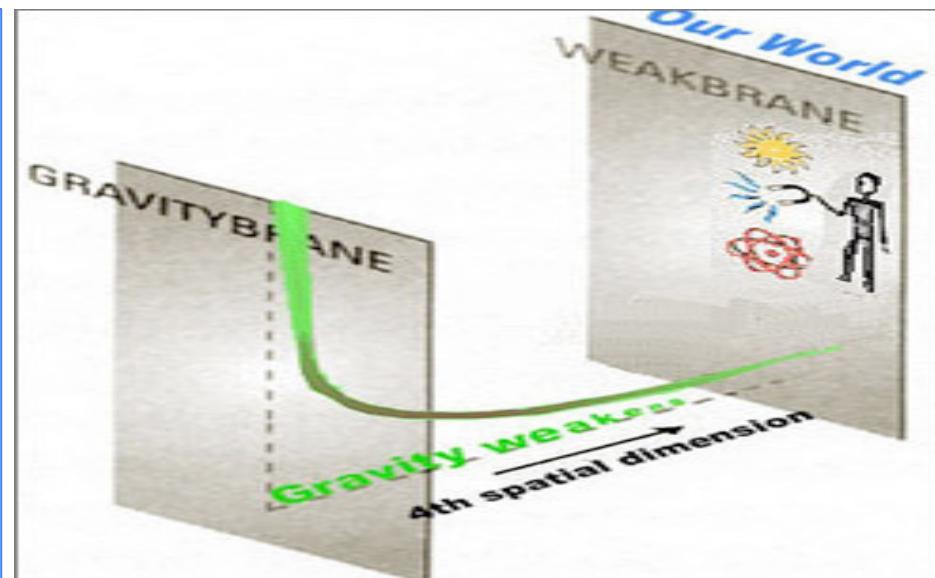
Some Theoretical Models for di-Higgs Resonances

Warped Extra Dimensions

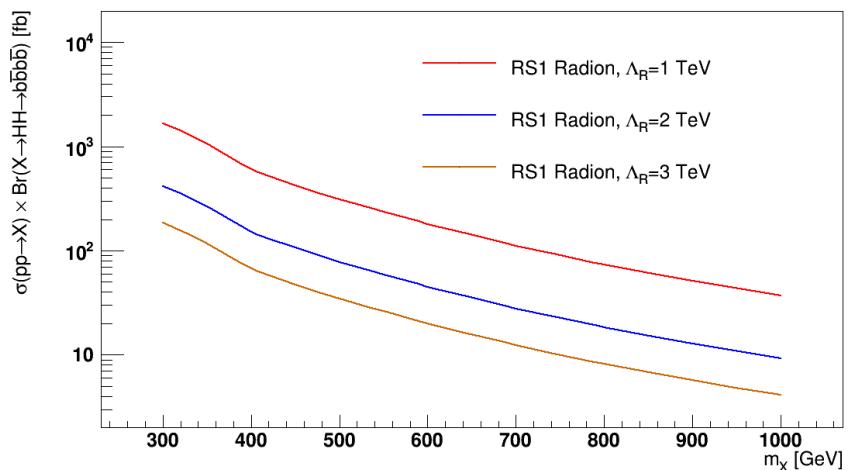
- A Randall Sundrum (RS1) warped extra dimension model requires a scalar radion to stabilize length of extra dimension
[[Goldberger Wise mechanism](#)]
- A radion of mass above 250 GeV can decay to two SM Higgs.
[[Radion Phenomenology](#), Csaba Csaki et al]

Generic Two Higgs Doublet Models

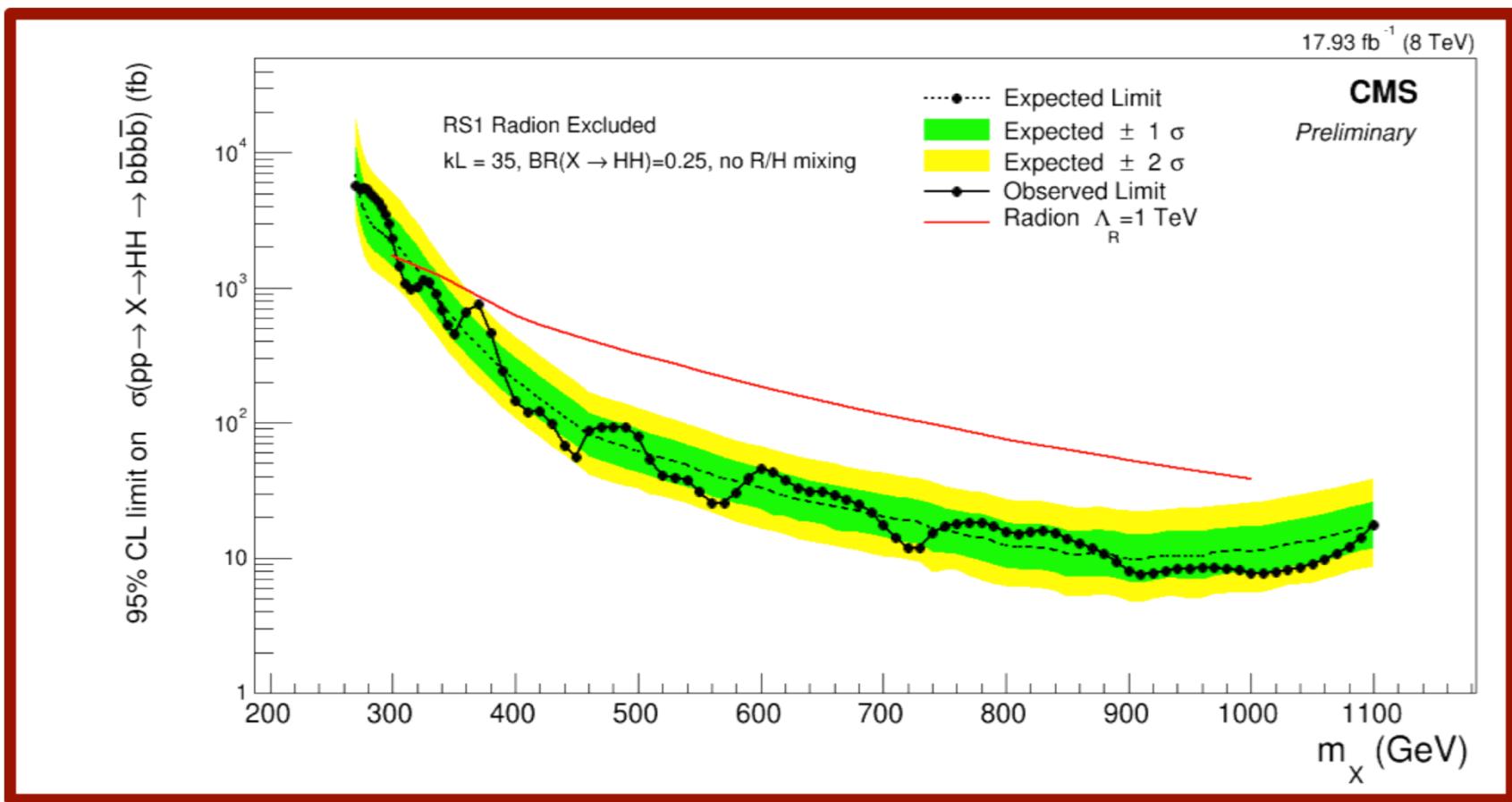
- 5 Higgs bosons: H, h, A, H^-, H^+ (MSSM)
- If h corresponds to the boson we found, $H \rightarrow hh$ is possible



Theoretical Cross Sections of the Radion



Unblinded Upper Limits



Observed and expected upper limits on the cross section for a narrow-width di-Higgs resonance decaying to four b-jets at 95% confidence level with 17.93 /fb of 8 TeV data computed using the CL_s method.

The RS1 radion in WED scenario $kL = 35$, elementary top, no radion-Higgs mixing with $\Lambda_R = 1$ TeV is excluded between 300 GeV and 1 TeV.