Introduction to HEP

University of Liverpool Particle Physics Summer School

16th of August 2021

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Who am I?

- Born and raised on the Wirral, Merseyside
- Undergraduate MPhys degree at University of Liverpool
- Postgraduate research student (PhD) at UoL
- Currently working onsite at CERN
- Dogs, playing football, plant mum and food

Introduction to HEP

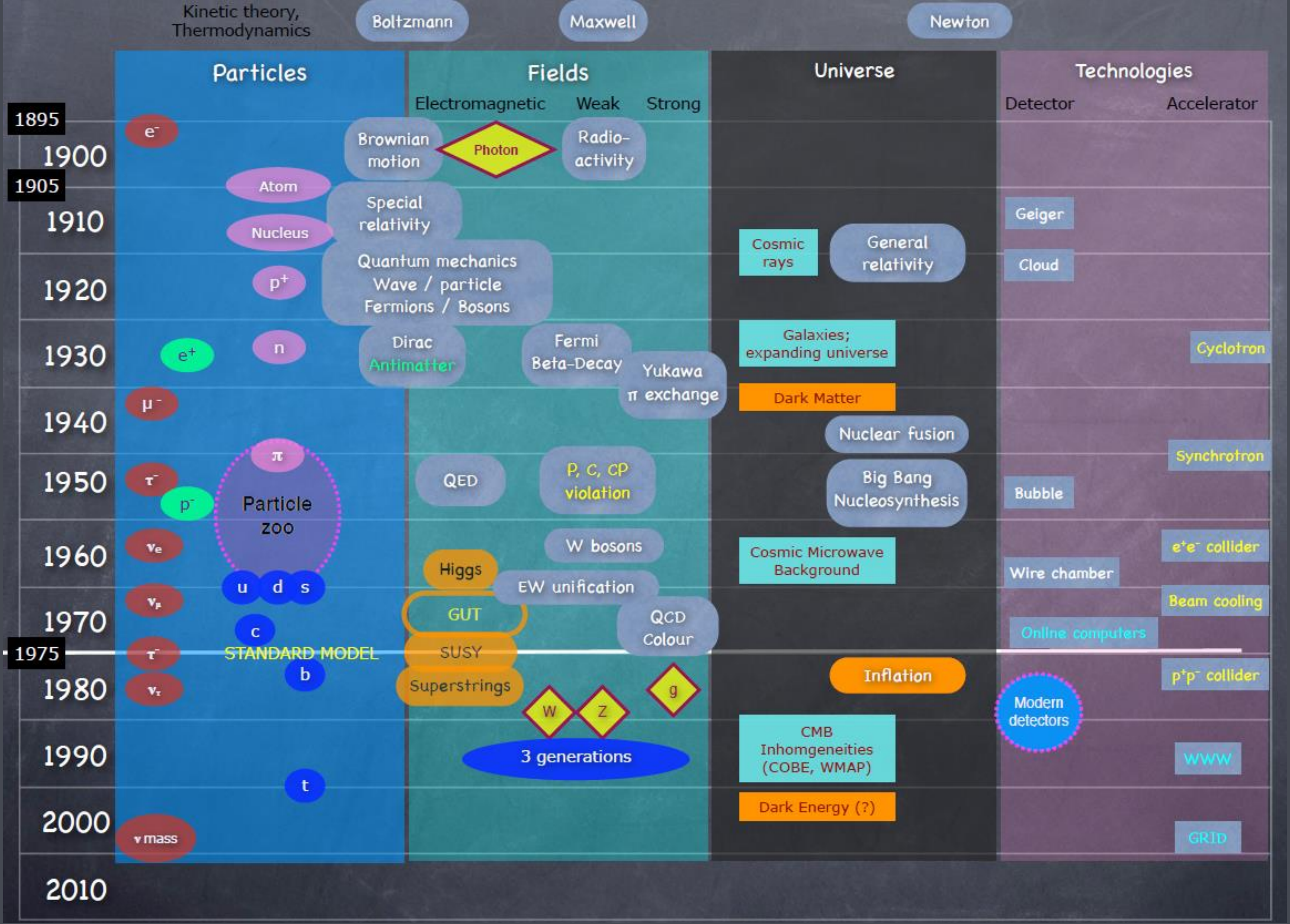
- What is HEP?
- The conclusion of 1800s/1900s HEP and why it was wrong
- What’s left to find?
- How are we finding it?
  - Current facilities and beyond
- The HEPtathlon quiz

What is HEP? High Energy Physics!

"HEP explores what the world is made of and how it works at the smallest and largest scales, seeking new discoveries from the tiniest particles to the outer reaches of space"

Address to the British Association for the Advancement of Science, 1900 said:

"There is nothing new to be discovered in physics now, all that remains is more and more precise measurement"



Kinetic theory, Thermodynamics
Boltzmann
Maxwell
Newton
Particles
Fields
Electromagnetic
Weak
Strong
Universe
Technologies
Detector
Accelerator
1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010
e⁻
Atom
Nucleus
p⁺
n
e⁺
μ⁻
π
τ⁻
p⁻
Particle zoo
νe
u d s
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c
STANDARD MODEL
τ⁻
b
ντ
t
ν mass
Brownian motion
Photon
Radio-activity
Special relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Dirac
Antimatter
Fermi Beta-Decay
Yukawa π exchange
QED
P, C, CP violation
W bosons
Higgs
EW unification
GUT
QCD Colour
SUSY
Superstrings
W
Z
g
3 generations
Cosmic rays
General relativity
Galaxies; expanding universe
Dark Matter
Nuclear fusion
Big Bang Nucleosynthesis
Cosmic Microwave Background
Inflation
CMB Inhomgeneities (COBE, WMAP)
Dark Energy (?)
Geiger
Cloud
Cyclotron
Synchrotron
Bubble
e⁺e⁻ collider
Wire chamber
Beam cooling
Online computers
p⁺p⁻ collider
Modern detectors
WWW
GRID

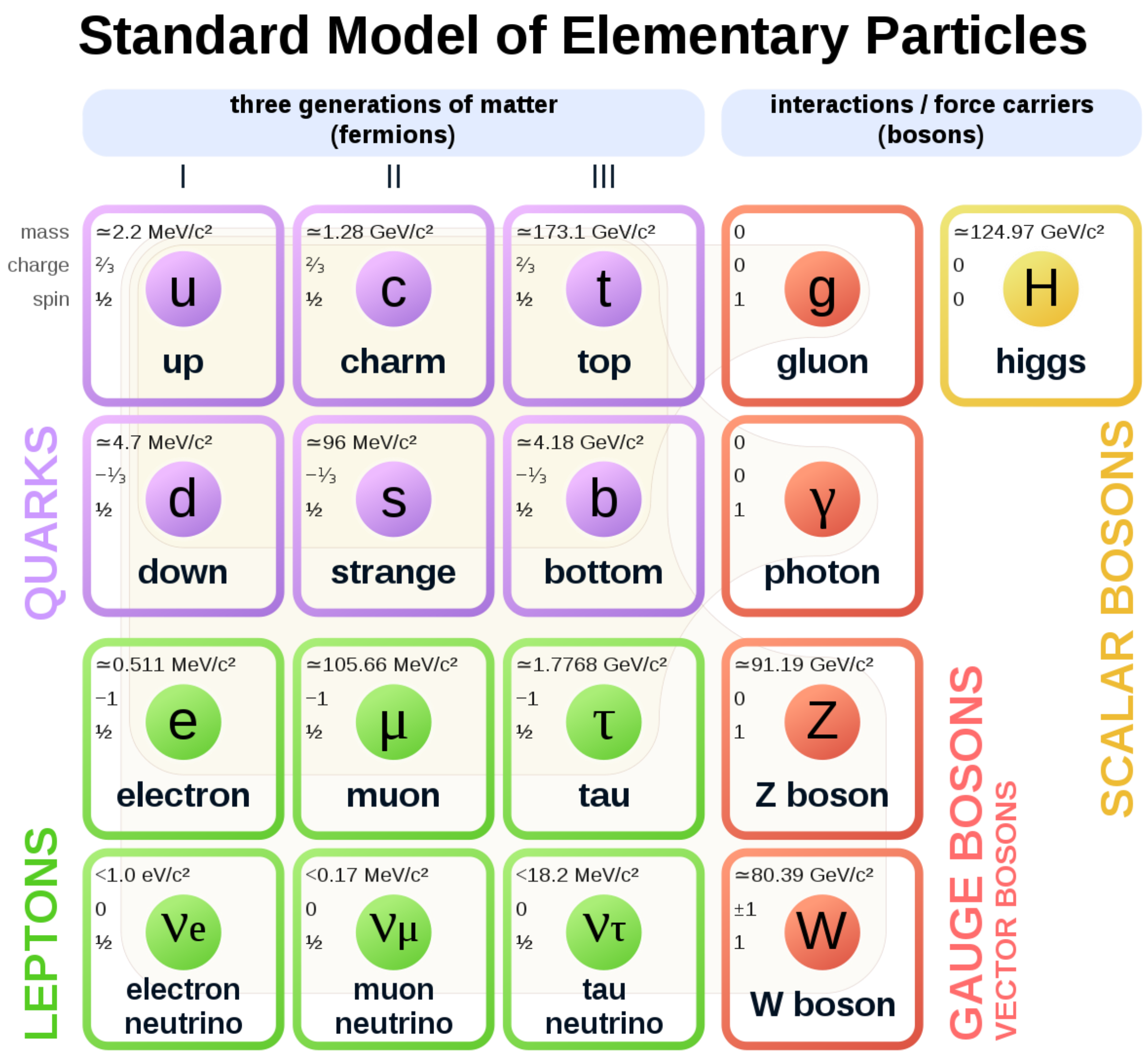
1900s

- Universe was known as only our solar system and our galaxy’s stars
- The sun’s energy production was unknown
- The structure of atoms and nuclei was unknown
- Only two fields where known: gravitational and electromagnetic

As we know, there was so much more to understand!

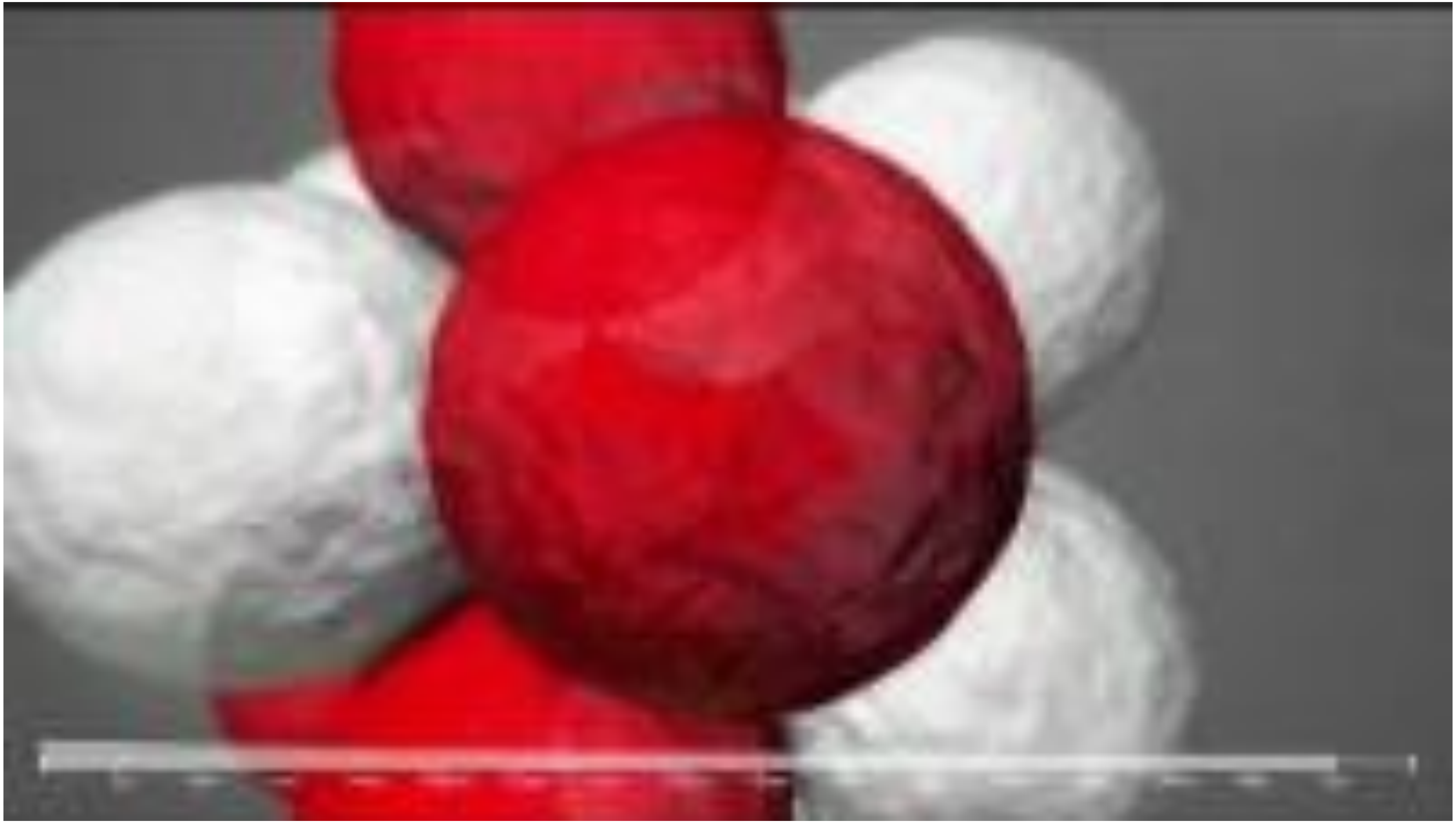
There are still unanswered questions…

- Dark matter?
- Dark energy?
- Gravitons?
- Unified forces?
- Antimatter/matter discrepancy



Just for some context…

https://youtu.be/7WhRJV_bAiE

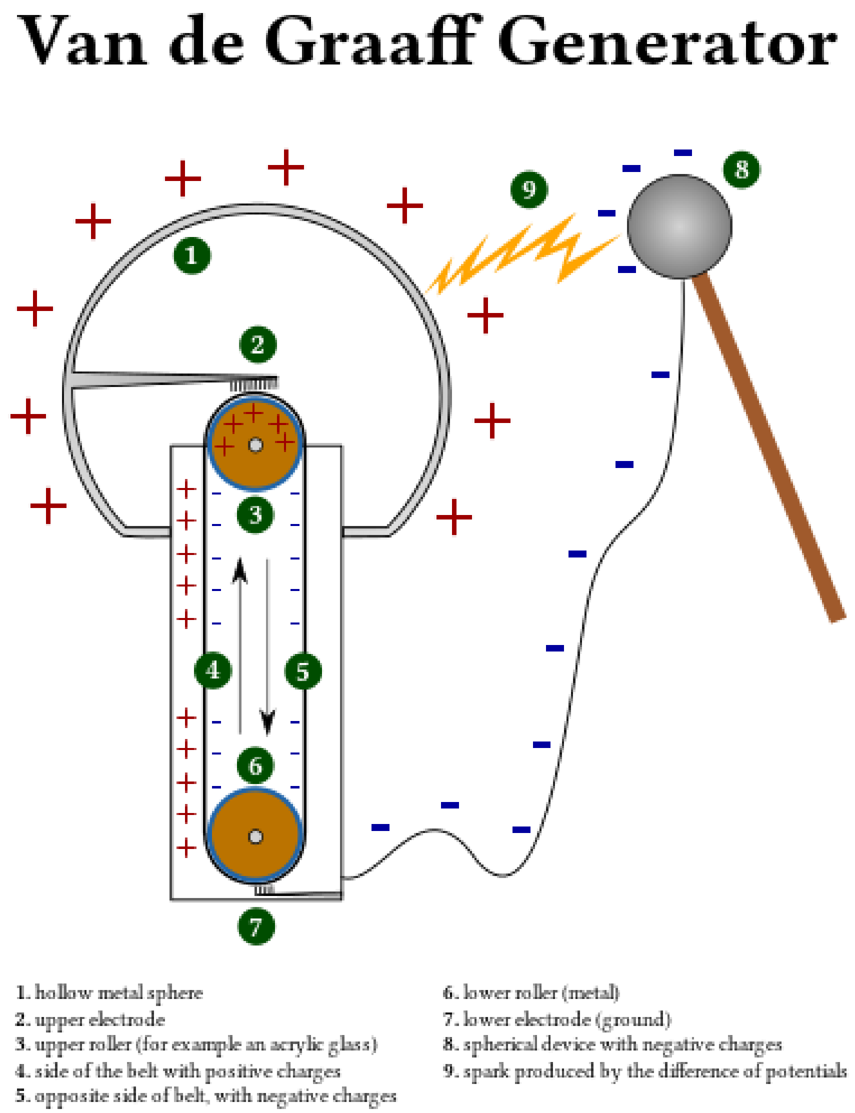


Acceleration and Current Facilities

- Beginnings of acceleration
- Circular accelerators
- CERN
- The LHC's main detectors
- Linear accelerators
- Non-accelerator based facilities
- The future of HEP

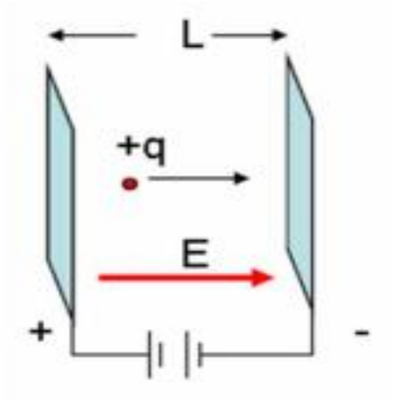
Then vs Now

- There are many, many HEP facilities around the world. Easily 100+
- Particle accelerators are used to:
  - Study universe origins
  - Investigates subatomic structure
  - Advance medicine
- They can be split according to the velocity of particles that are accelerated and by the particle mass
- An example of an early accelerator is a Van der Graaf
- More recently, cyclotrons and synchrotrons

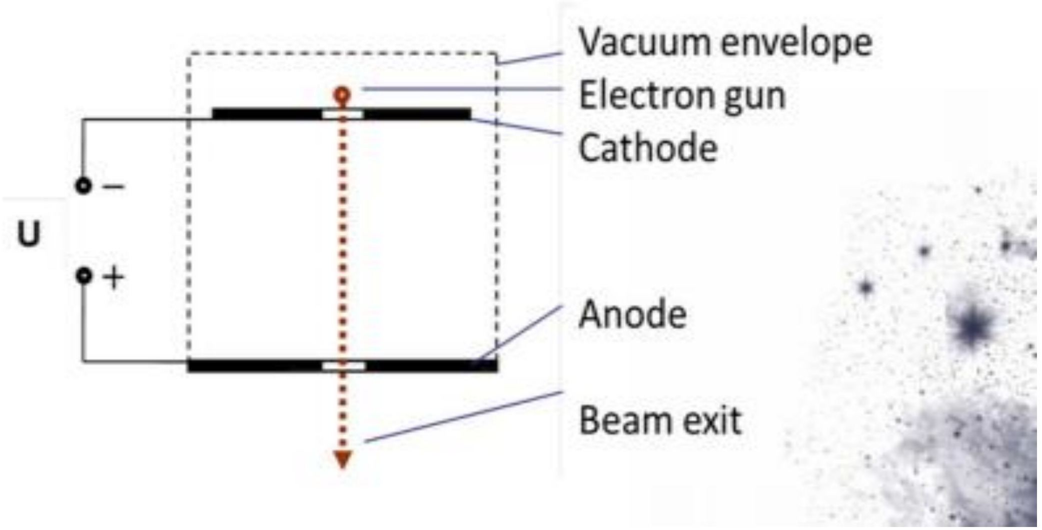


Direct Accelerators: transformers

- Direct accelerators are machines in which accelerated particles move in a constant electric field.
- They gain energy (eV) equal to the potential difference (V) applied.



$$\Delta W = qV_0$$



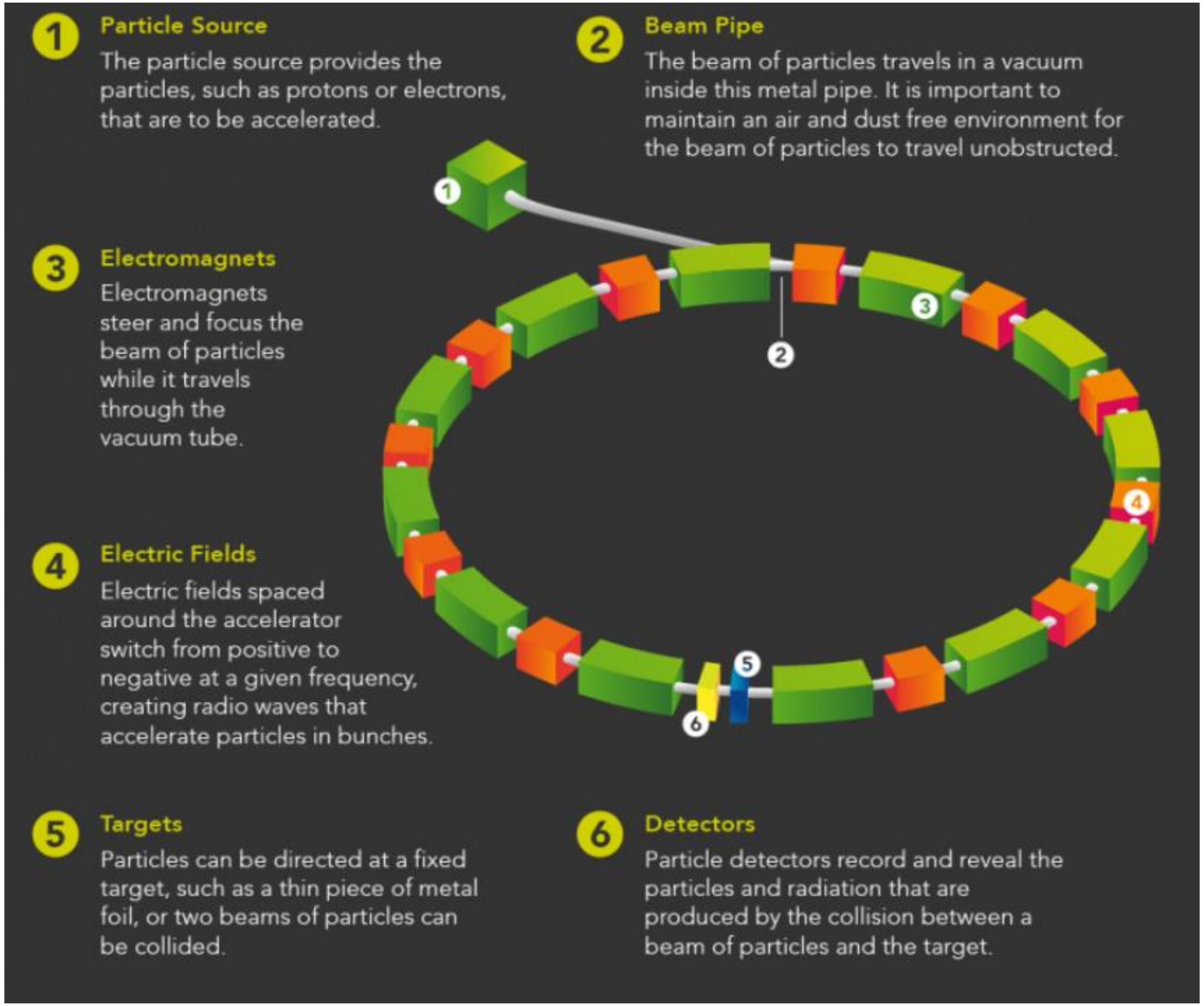
- This can be used for the acceleration of electrons, protons and ions.

Direct Accelerators: Transformers

- Early examples include the Cockcroft-Walton generator and the Van der Graaf generator
- Daresbury laboratory in Cheshire housed a very large Van der Graaf based generator within the Nuclear Structure Facility (NSF) from 1981-1993.
  - Operated at 20 MV
  - Accelerated 80 difference ion beans for experimental use
  - Now home to the Cockcroft Institute focusing on accelerator physics

Circular Accelerators

- Particle accelerators produce a beam of charges particles that can be used for a variety of research areas
- Most often used:
  - Protons
  - Electrons
  - Muons
  - Heavy ions (eg lead, Pb, or uranium, U)
- But also antimatter! (AEGIS, ASACUSA, ALPHA at CERN)

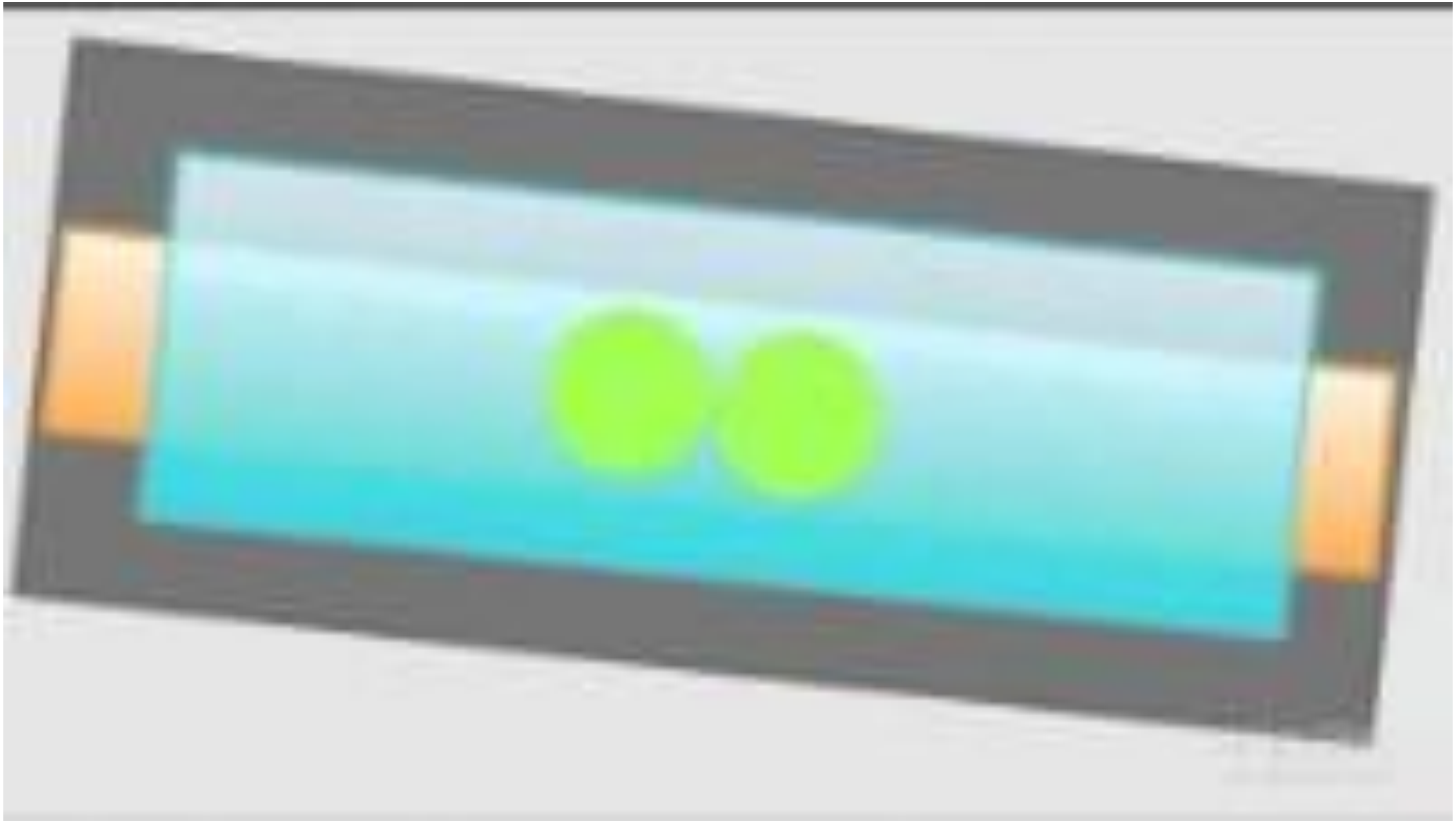


CERN – the European Organisation for Nuclear Research

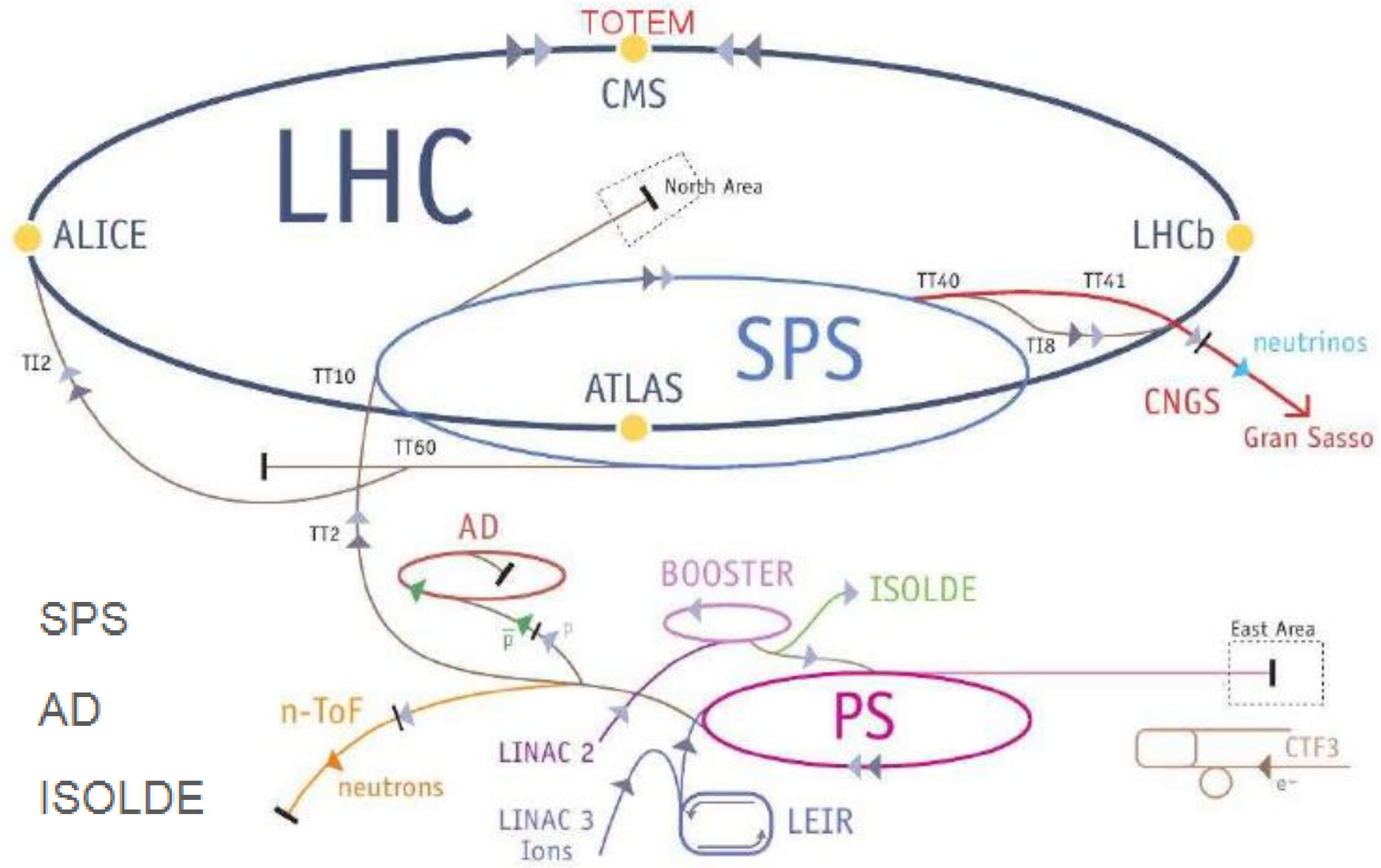
- 27km
- 100m underground
- Primarily a proton-proton (PP) collider
- Consists of RF cavities and magnets for acceleration and beam focusing
- 4 main detectors:
  - ATLAS
  - CMS
  - ALICE
  - LHCb

What actually happens at CERN?

https://youtu.be/QEfFy1EJxT0



CERN: accelerator complex

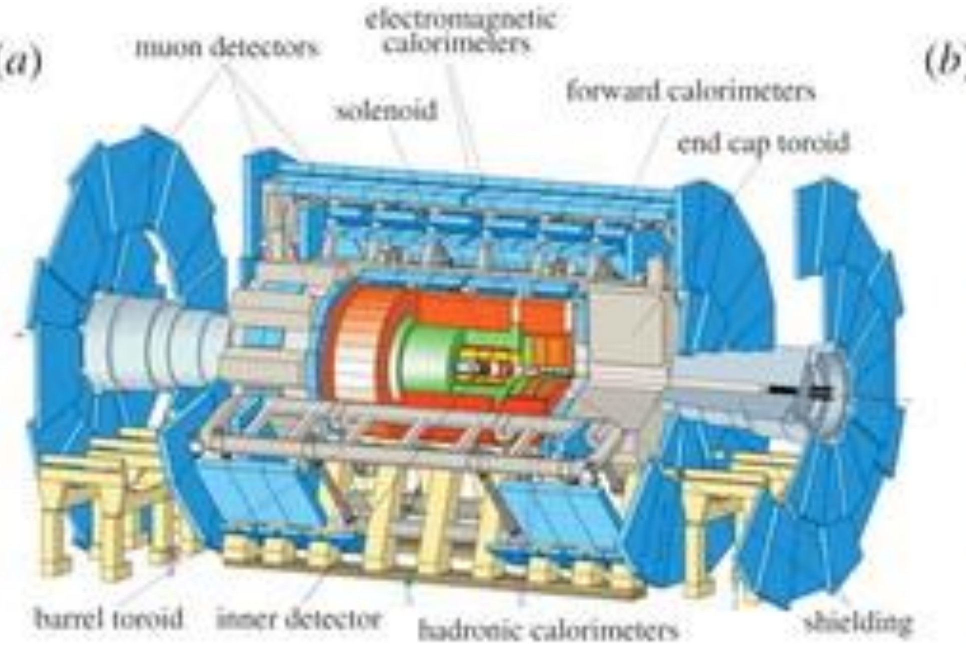


Super Proton Synchrotron	SPS
Anti-proton Decelerator	AD
Isotope Separator OnLine DEvice	ISOLDE
Proton Synchrotron Booster	PSB
Proton Synchrotron	PS
LINear ACcelerator	LINAC
Low Energy Ion Ring	LEIR
CERN Neutrinos to Gran Sasso	CNGS

ATLAS

- A Toroidal LHC Apparatus
- 46m long
- 25m diameter
- 7000 tonnes (the Eiffel tower is 7300 tonnes)
- One in 10^{13} interactions produces a Higgs -> ZZ where Z -> e- e+
- Leading the search for supersymmetry particles (SUSY)

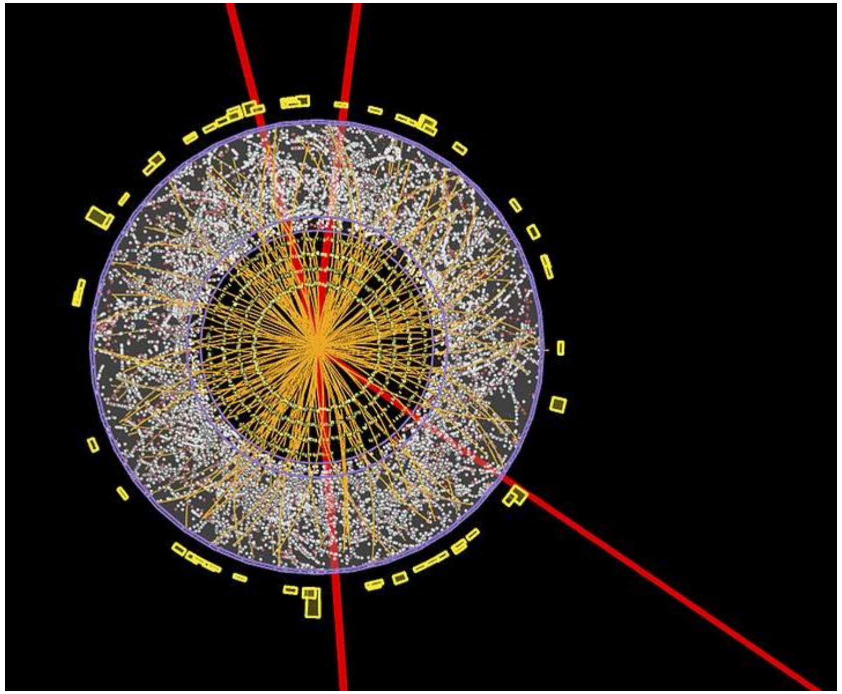
(a)



(b)

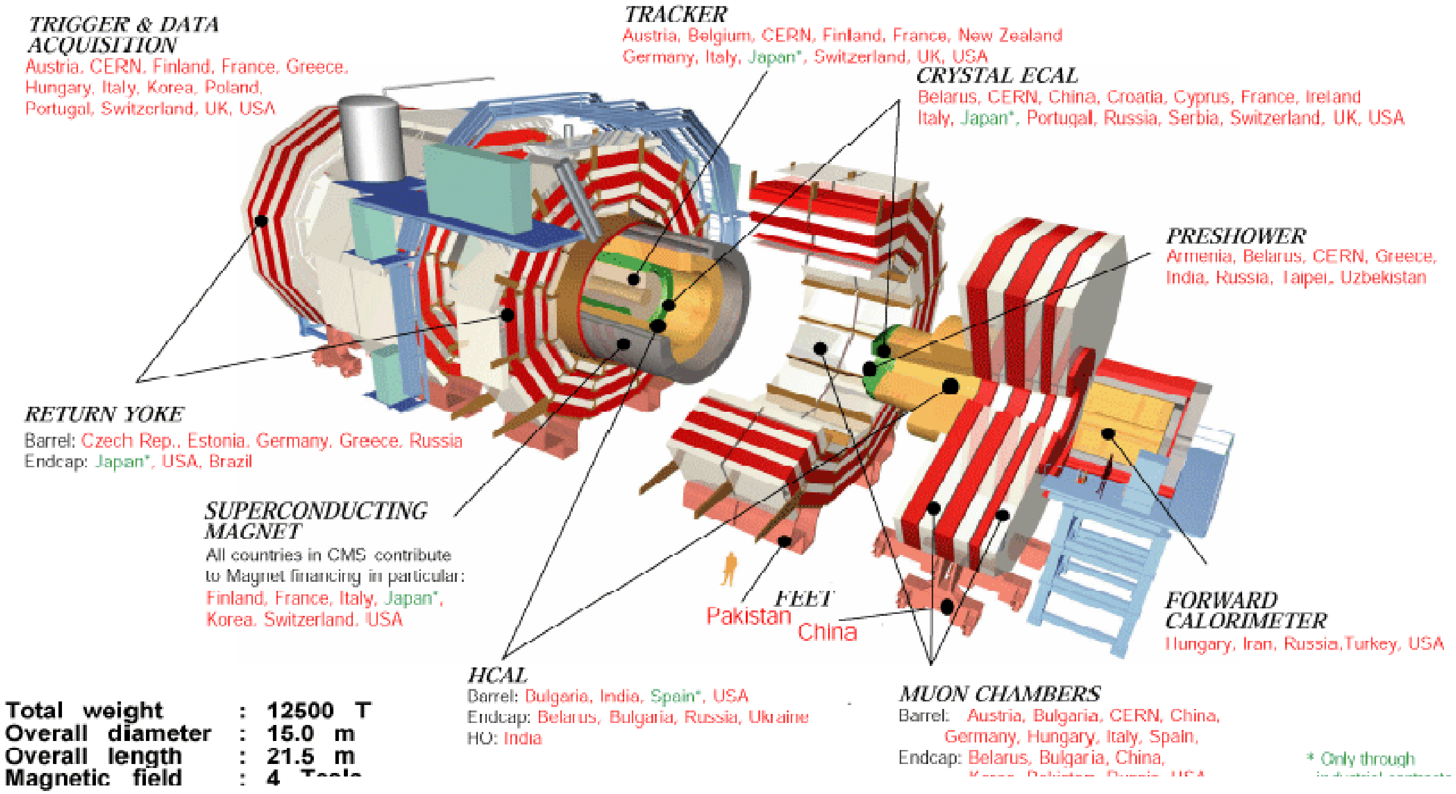
- 3200 terabytes (terabyte = a million megabytes) of data per year

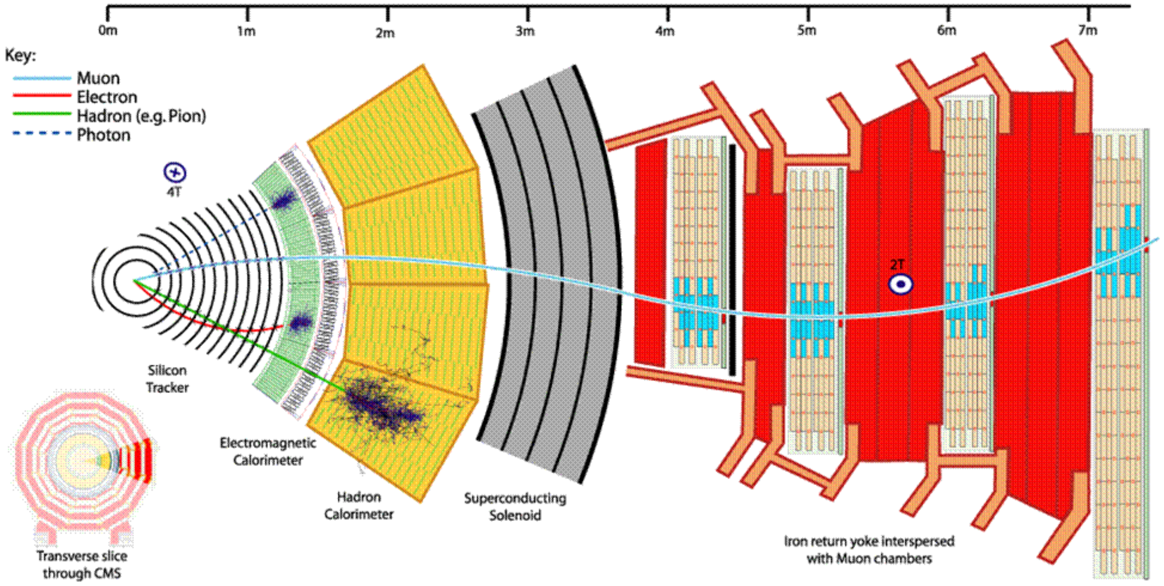
  That is 600 years worth of back to back songs
- ~5500 scientists across 41 countries



CMS

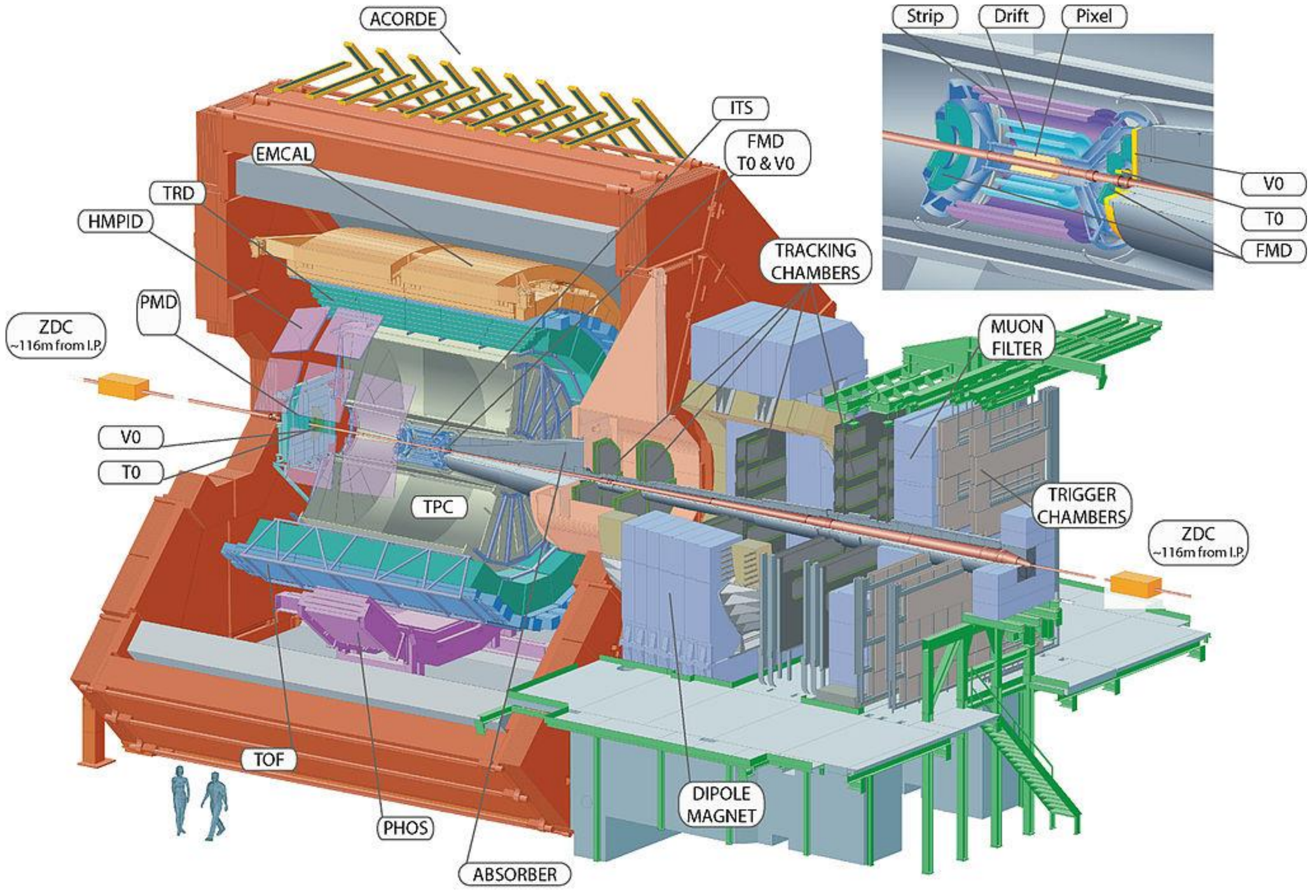
- Compact Muon Solenoid
- 14,000 tonnes
- 15m diameter
- 21.5 meters long
- Made of 15 large slices with different parts of the detector formed around the central beam pipe.
- ~2800 scientists across 43 countries

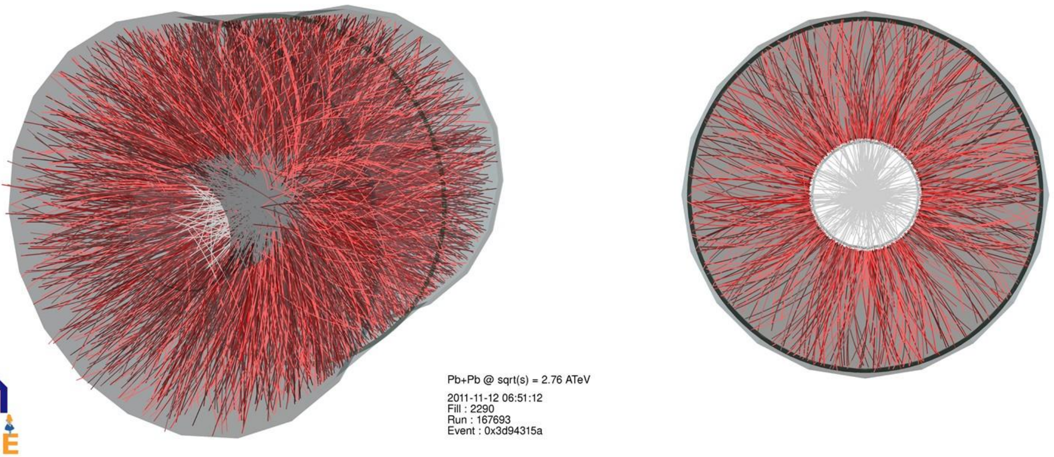




ALICE

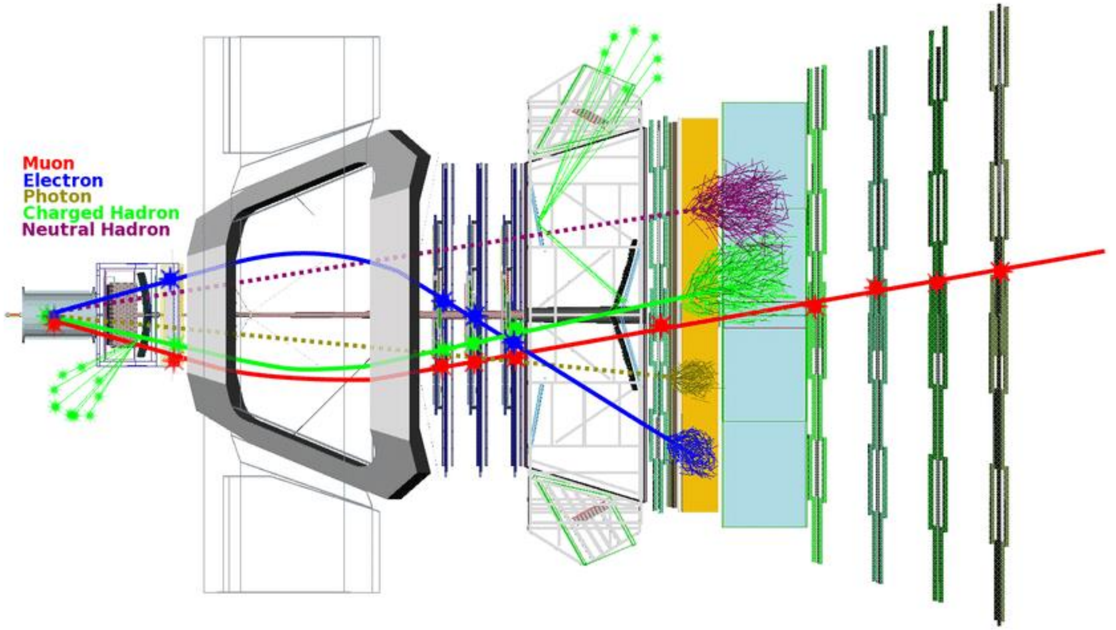
- A Large Ion Collider Experiment
- Dedicated heavy-ion physics detector
- Designed to study the physics of strongly interacting matter at extreme densities, where quark-gluon plasma forms.
- 10,000 tonnes
- 26m long
- 16m high
- ~1000 scientists in 30 countries

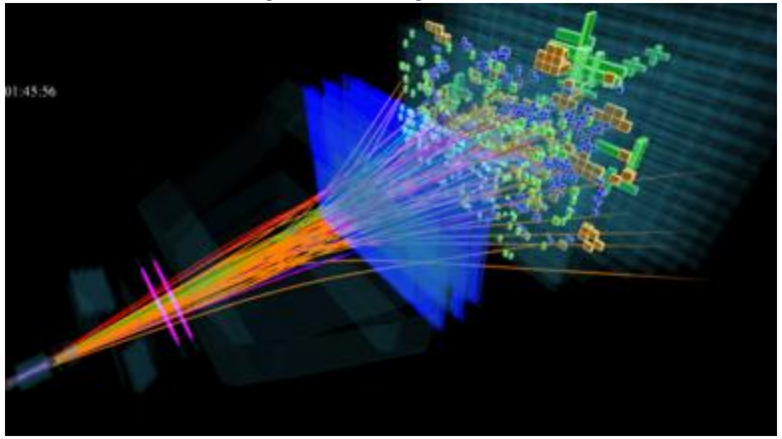


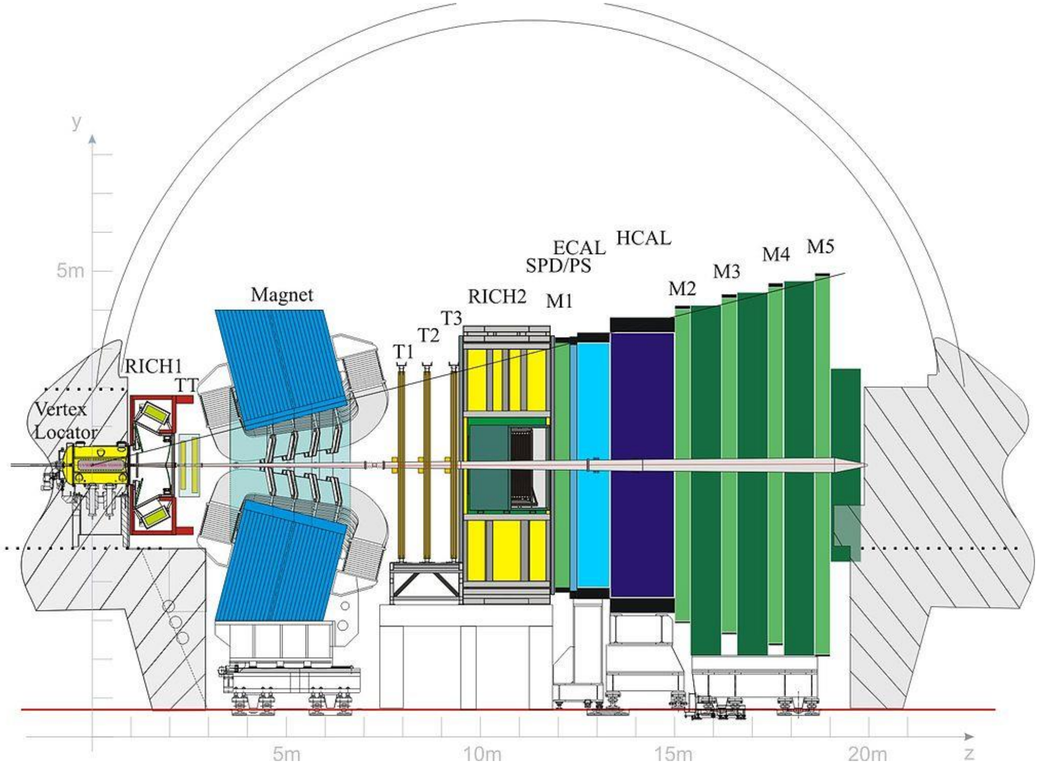


LHCb

- Large Hadron Collider Beauty
- CP (charge-parity) violation, flavour and electroweak studies
- A forward region detector which differs from the other hermetic detectors
- ~1400 scientists across 18 countries
- Major focus on determining why we have a matter antimatter discrepancy
- 21 meters long
- 10 meters high
- 5600 tonnes



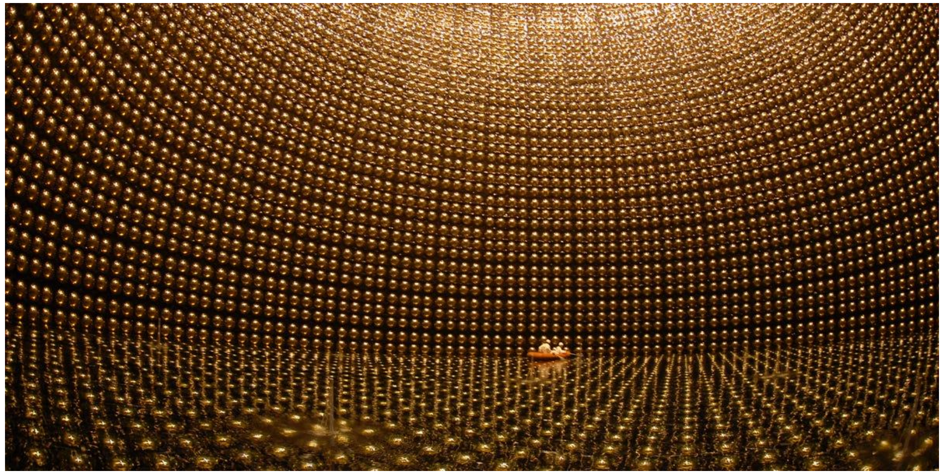




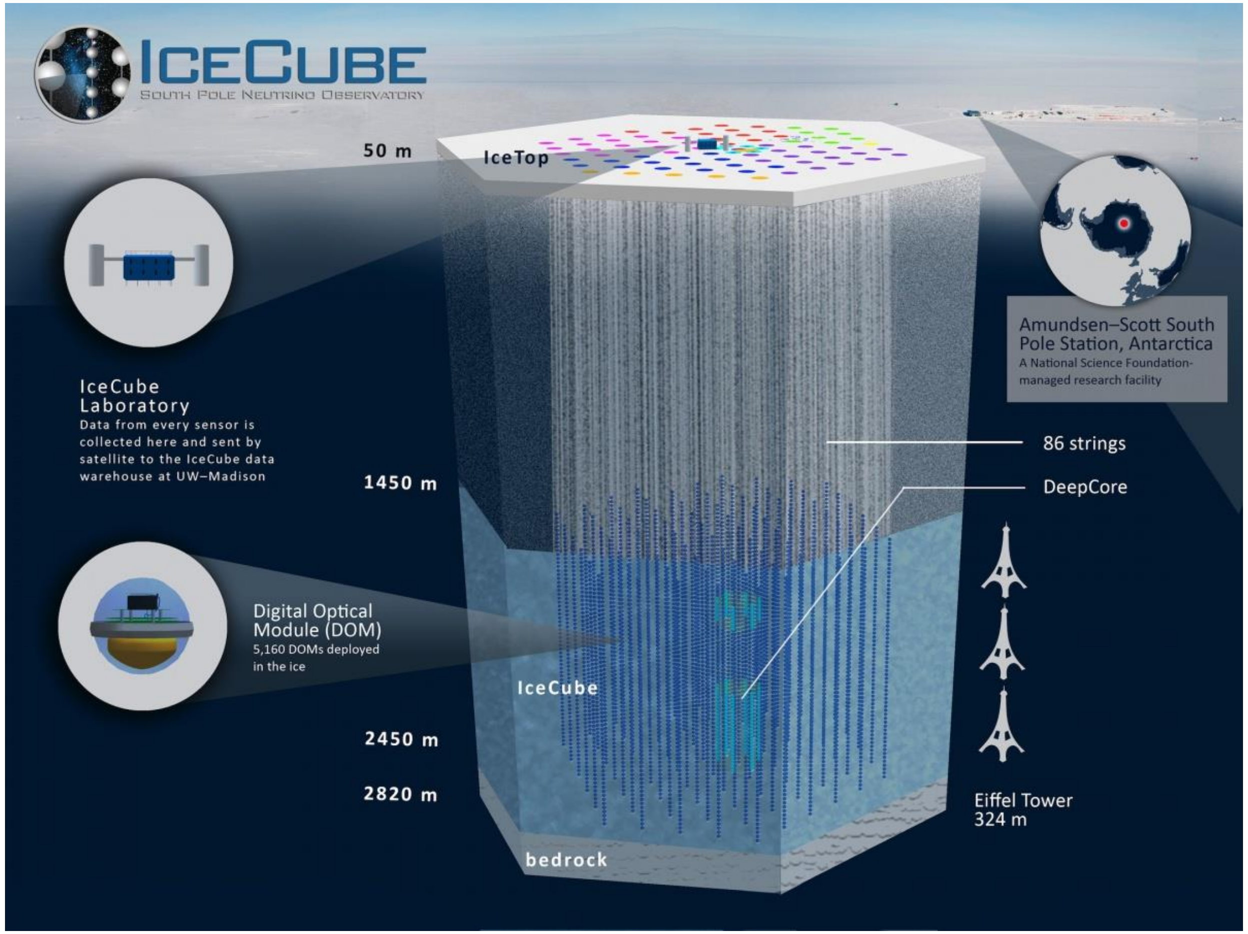
Linear Accelerators

- There are two main purposes to linear accelerators:
  - Medical applications
  - Fixed target experiments
- Linear accelerators are used as part of the preparation process of beams in collider experiments too
- In fixed target experiments, a particle beam collides with a target that is stationary in the laboratory frame, producing secondary particles for study
- These experiments are highly specialised and focus on precision measurements
- They require very high statistics due to often measuring ultra-rare decays
- Linear Accelerators are very useful in medical oncology applications, such as proton therapy for cancer treatments

Non-accelerator based facilities



- Neutrino observatory's are non accelerator based facilities that study neutrinos specifically
- Examples include:
  - IceCube in Antarctica
  - Super-Kamiokande, Japan

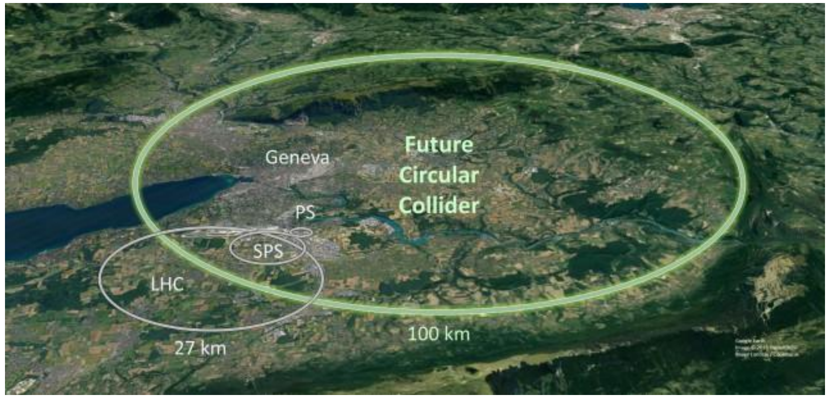


- These experiments are huge, they need to be to detect a significant number of neutrinos
- They are often remote (IceCube in the south pole) and/or underground (Super-K 1000m below) to isolate the detector and remove unwanted noise

Future of HEP

- Focus but board – don’t want to miss anything hidden!
- High-luminosity phase (HL-LHC) will operate 2027 to ~2040
  - Aim is to increase the number of collisions and target rare processes
  - 3 million Higgs bosons per year in 2017 to 15 million Higgs bosons per year in HL-LHC

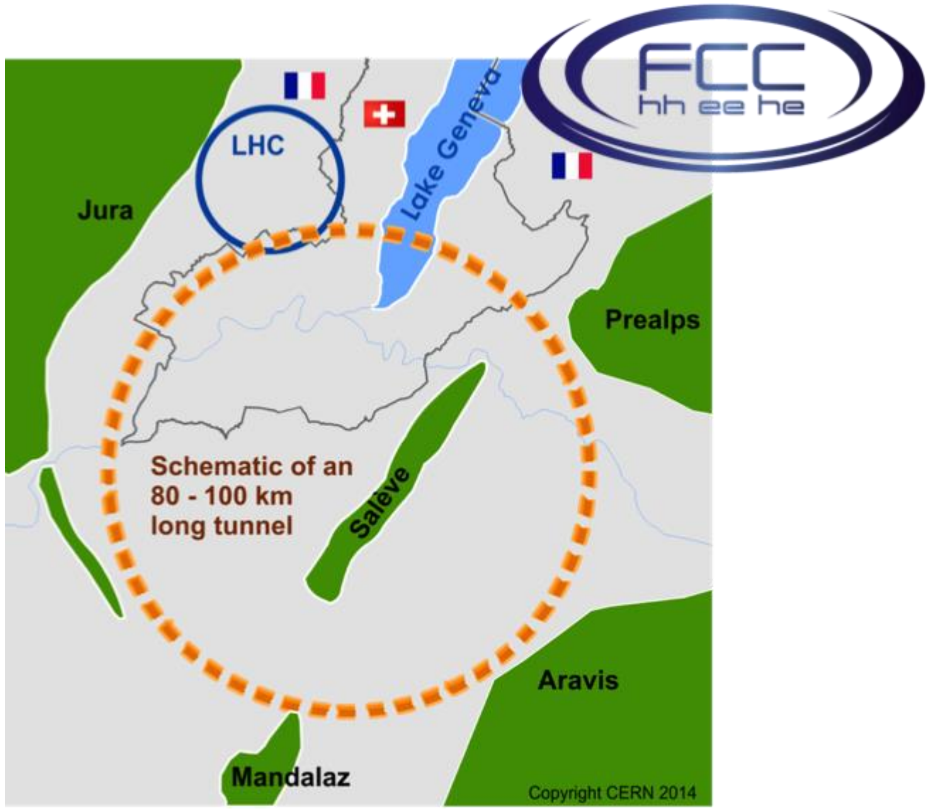
- The Future Circular Collider (FCC) will be 100km vs 27km and reach collision energies of 100TeV



Conclusion

- We've discovered amazing things over the past 100 years
- We've built huge colliders all over the world, I've focused a bit more on CERN today
- There are still unknowns left to discover
- The future is looking bright!

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$



Quiz time!

1. Which LHC experiment is the heaviest?
   ATLAS, CMS, ALICE or LHCb

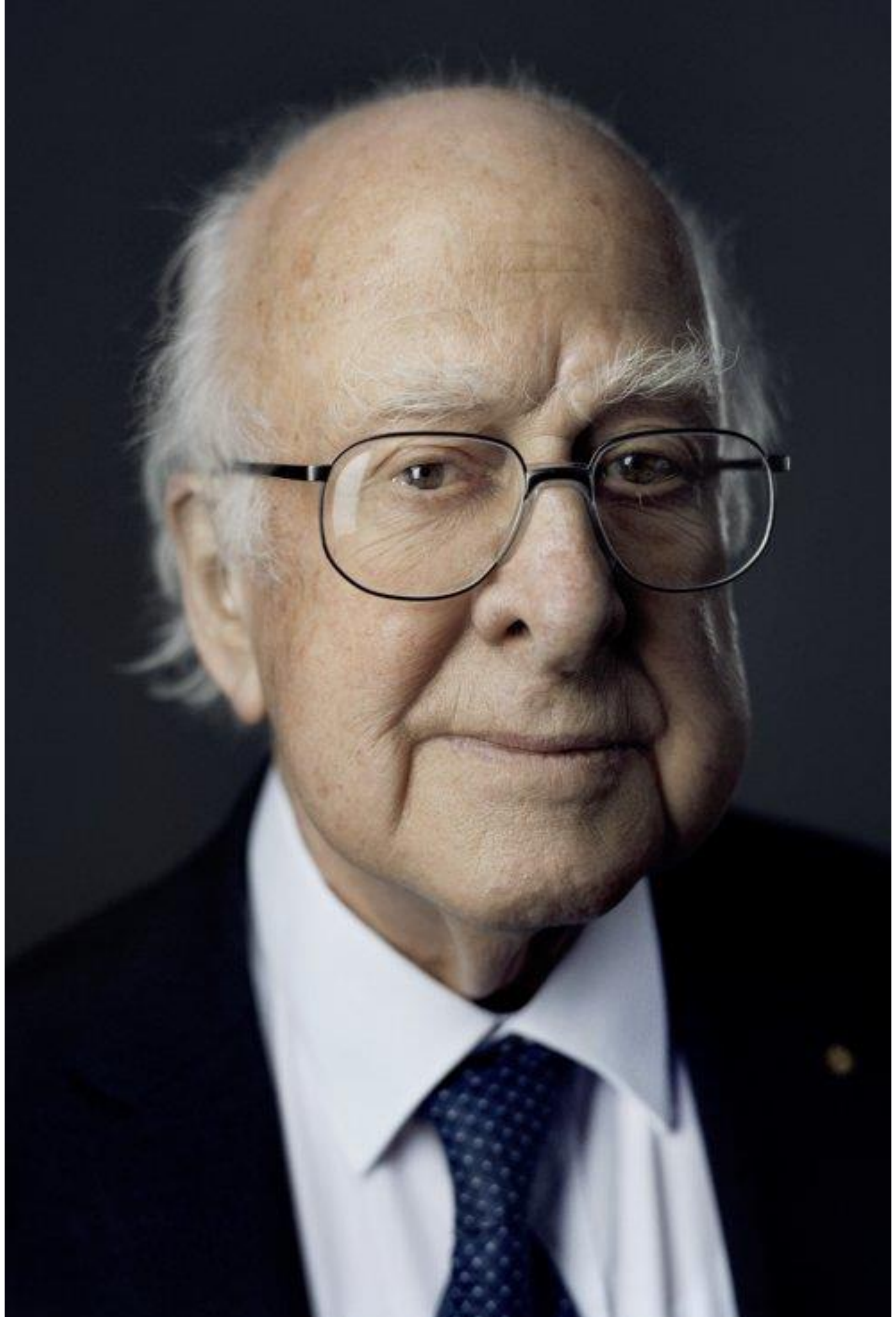
2. Out of the four main LHC experiments, which is the ‘odd on out’ detector that has a different geometry? (ie isn’t hermetic)
   ATLAS, CMS, ALICE or LHCb

3. In what year was the Higgs boson discovery announced by ATLAS and CMS?

4. What does FCC stand for? It’s the successor of the LHC!

Quiz time!

5. Who is this person?



Quiz time!

6. In what country is CERN located?

7. Where in the world is Fermilab located?

8. Daresbury laboratory houses what type of accelerator which was in use until the 90s?

9. What unit is used to measure the total amount of data stored by CERN from all it's experiments so far?

Megabyte GB   Terabyte TB (1000 GB)   Petabyte PB (1000 TB)   Zettabyte ZB (1,000,000 PB)

10. Estimate the number of people (including scientists, engineers and admin staff) work at CERN. Within 10% gets a point!