# Introduction to Particle Physics

## Special Particle Physics MasterClass

**Organized by the International Particle Physics Outreach Group (IPPOG) & Women in Technology at CERN (WIT)**

**Date: 13/02/2025**

**Speaker: Joni Pham (ARC Centre of Dark Matter, University of Melbourne & ATLAS Collaboration)**

# 1. What is Particle Physics?

- “Particle physics is a branch of physics that studies the **elementary constituents of matter and radiation, and the interactions between them.** It is also called "high energy physics", because many elementary particles do not occur under normal circumstances in nature, but can be created and detected during energetic collisions of other particles, as is done in particle accelerators. Particle physics is a journey into the heart of matter”. (Floratos, E 2025)

- The ultimate goal is to answer the questions: what are we made of, where did we come from, and where are we going to?

- To study Particle Physics is **to see the invisibles.**

- The study of Particle Physics at CERN extends beyond the elementary particles, but also nuclear & atomic physics, condensed matter physics, medical physics, and a variety of engineering and technology.

CERN

# 2. Applications of Particle Physics

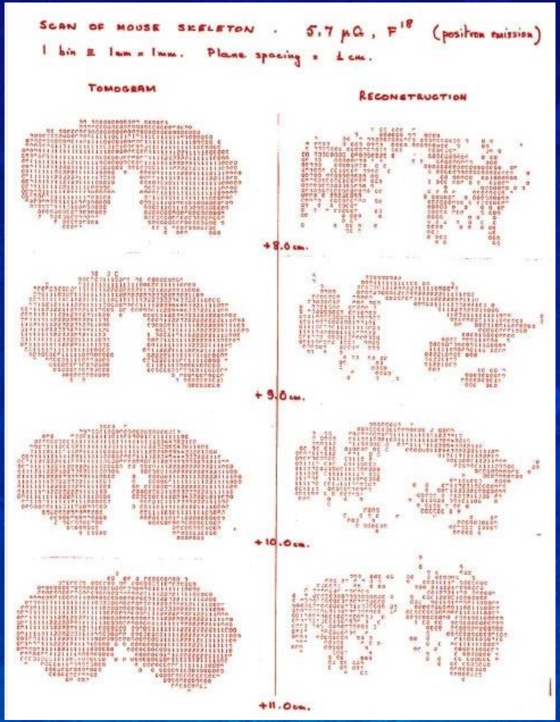
- X-ray imaging and further applications in medical & biological research
- https://www.epa.gov/radtown/women-radiation-history-rosalind-franklin


Joni Pham (CDM, University of Melbourne & ATLAS Collaboration)

# 2. Applications of Particle Physics

- First image of a mouse using a PET (positron-emission tomography) camera (1977) by Dr Marilena Bianchi, David Townsend & Alan Jeavons (CERN).

- After the initial success, Jeavons and Townsend devoted their careers to improving medical imaging. Later, Townsend and co-workers in the US suggested to combine **PET-CT (computed tomography)** to see both metabolic and anatomic information. This was a major breakthrough for **cancer diagnosis and treatment follow up**.



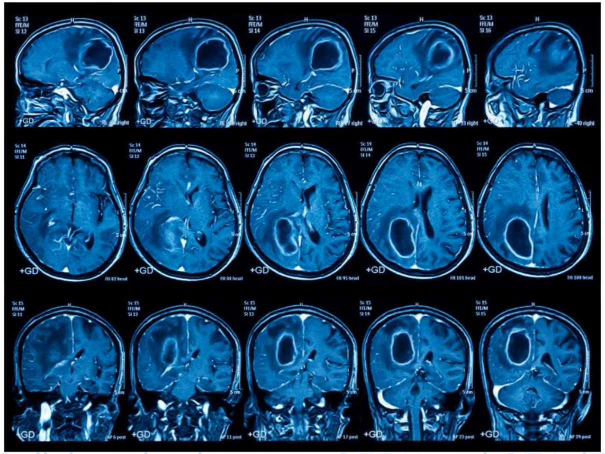

https://www.rgcirc.org/clinical-services/nuclear-medicine-services/basis-of-pet-ct-scan/


https://www.upstate.edu/ura/pet-ct-scan.php

# 2. Applications Particle Physics

**From LHC Magnets to High-Field MRI and Efficient Power Grids**

Success Story



Collaboration between CERN and CEA (French Alternative Energies and Atomic Energy Commission) on **high-field MRI magnets at NeuroSpin** to improve image resolution.

Superconductivity is also considered a key technology for high-efficient energy generation and transport.

**GaToroid - getting closer to affordable cancer therapy**

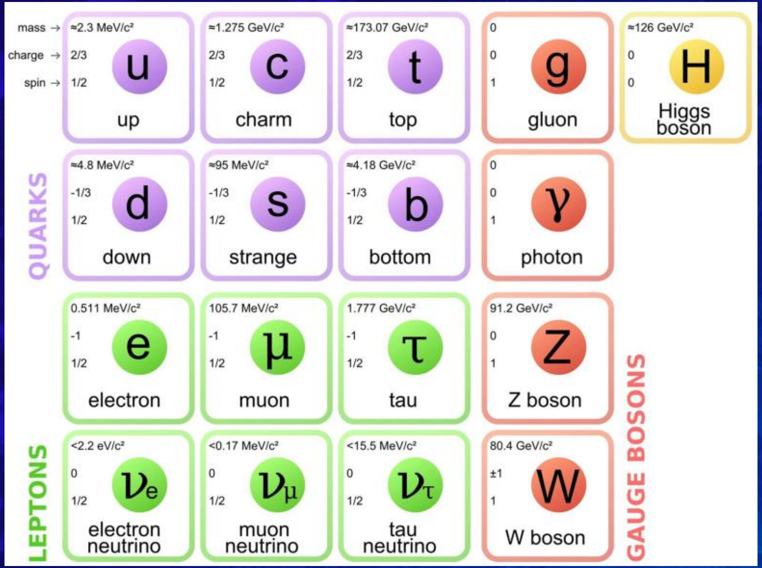
CERN has been contributing to developing technologies to improve hadron therapy for the past 30 years. Now, a team at CERN is working on new design concepts that would make the machines delivering hadron therapy much more compact and economically viable

16 JANUARY, 2025 | By Melanie Arnold

Luca Bottura, project lead of GaToroid, and Gregory Maury from the TE/MSC-SMT section are working on winding a coil of the demonstrator for GaToroid.

Hadron therapy for cancer treatments with the use of **novel superconducting and lightweight gantry, GaToroid**

# 3. The Standard Model (SM) of Physics



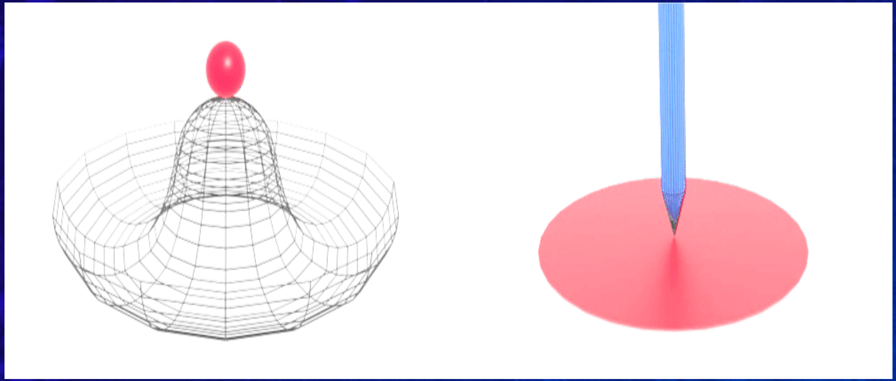

[The Standard Model of Physics]

- **Matter particles: quarks and leptons.** Each group consists of six particles, which are related in pairs, or “generations”. The lightest and most stable particles make up the first generation, whereas the heavier and less stable particles belong to the second and third generations.

- **Force carrier particles: bosons**
  3 of the fundamental forces (strong, weak, electromagnetic (EM)) result from the exchange of bosons. Each fundamental force has its own corresponding boson. Particles of matter transfer discrete amounts of energy by exchanging bosons with each other.

- **WZ discovery by UA1 & UA2** experiments of the SPS proton-antiproton collider resulted in the Nobel prize in Physics (1984) to Dr Simon Van der Meer & Carlo Rubia.

# 4. The Higgs Boson



The particle in the "Mexican hat" shape of the Higgs field (left) and the pencil standing on its tip (right) both show spontaneously symmetry breaking – symmetry is present, but only for a moment

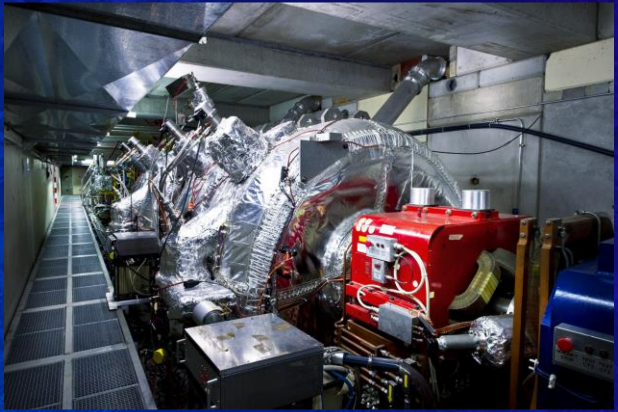
- SM is based on the notion of symmetries in nature -> Unification of the electroweak (EW) force.
- Problem: "The symmetries explained the EW force but in order to keep the symmetries valid, they forbid its force-carrying particles from having mass [...] The photon, which carries EM, we knew was massless; the W and Z bosons, carriers of the weak force, could not be." Fabio Cerutti.
- **Brout-Englert-Higgs mechanism (1964):** Higgs field + spontaneous symmetry breaking -> W & Z boson masses. Other elementary particles also acquire masses by interacting with the Higgs field, giving rise to the particle properties.
- **The discovery in 2012 by ATLAS + CMS** confirmed the BEH mechanism and the Higgs field.

# 5. Physics Beyond the Standard Model (BSM)?

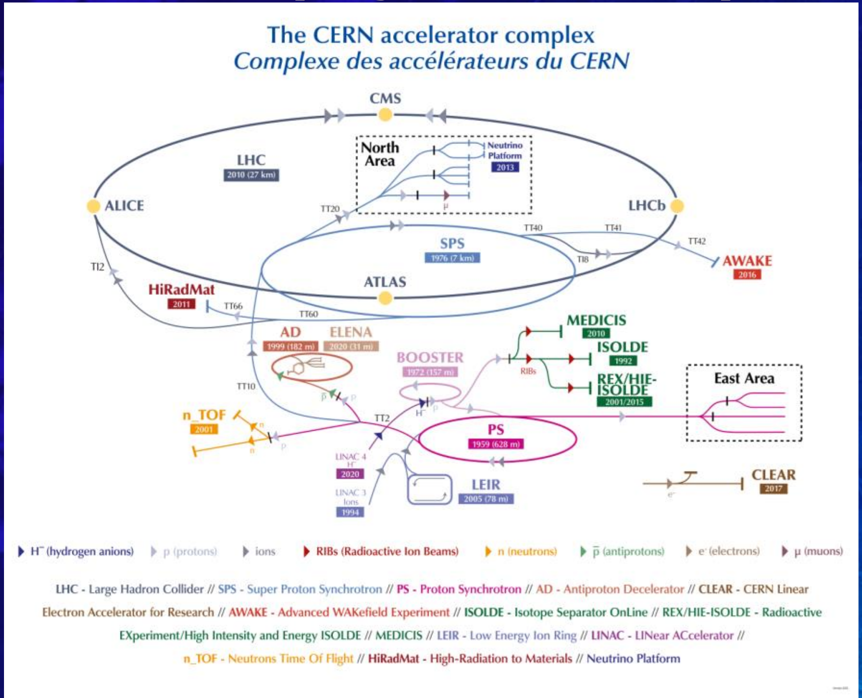
- Why is gravity so weak?
- What are dark matter and dark energy?
- Why was there an asymmetry between matter and antimatter?
- Neutrino oscillations? (How neutrinos can convert from one flavour to another and therefore have non- zero masses)

LHCb Experiment


AMS Experiment


Antimatter Factory

# 6. LHC physics: The path of protons/ions

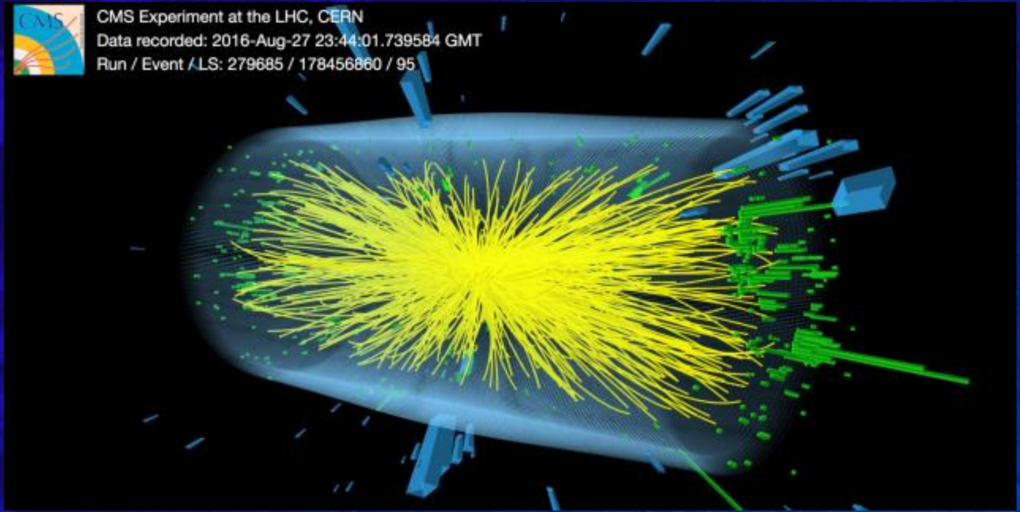


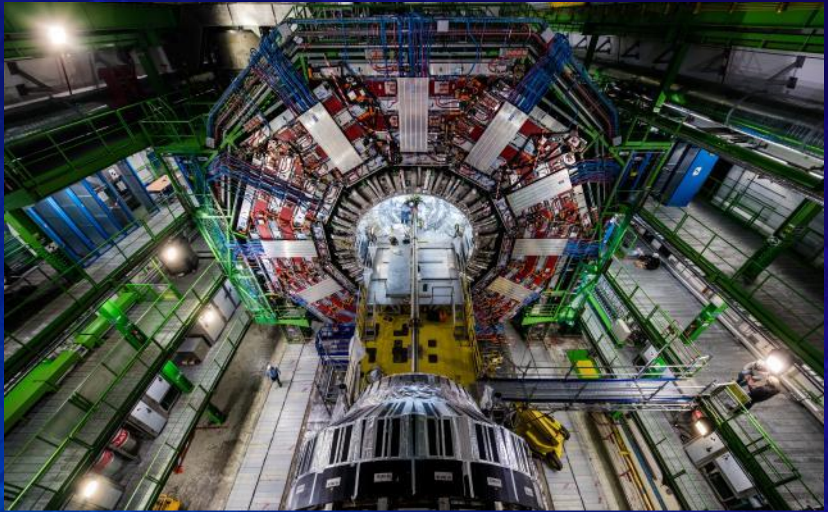


CERN accelerator complex

Complex of accelerators & decelerators

# 7. Collisions

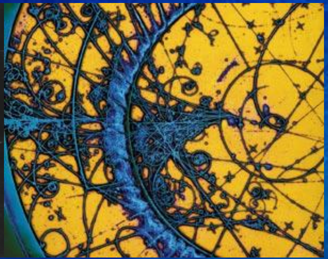


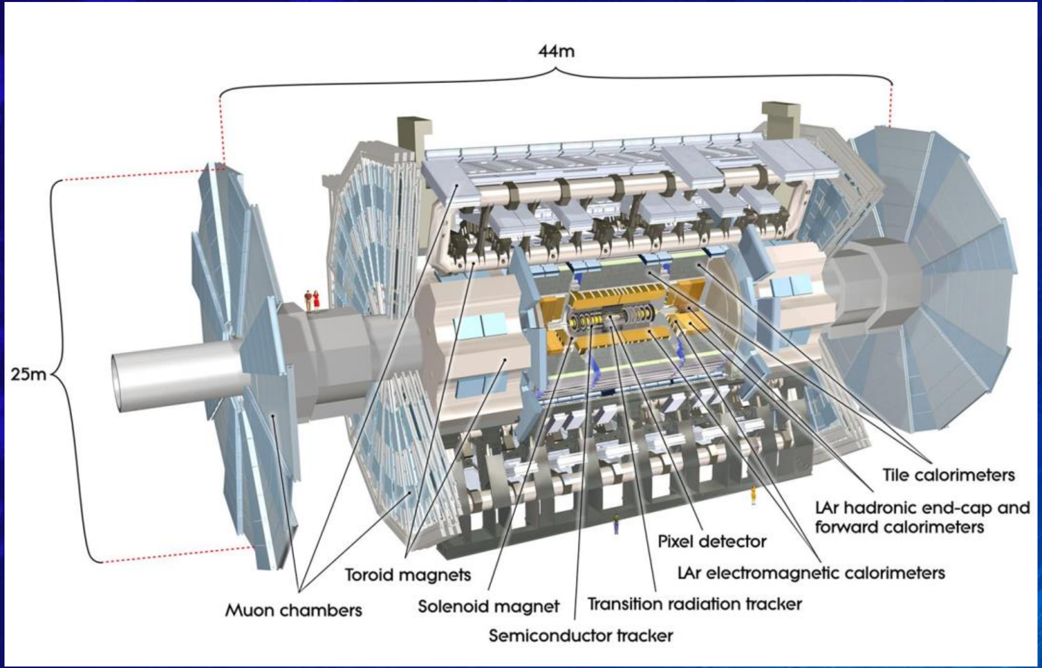
- Collisions happened inside 4 detectors: CMS, ATLAS, ALICE & LHCb every few ns
- E = mc^2 -> a spray of particles created after each collisions
- We do not directly observe the collisions but try to understand the processes from the traces left behind by the particles created from the collisions

# 8. From the bubble chamber

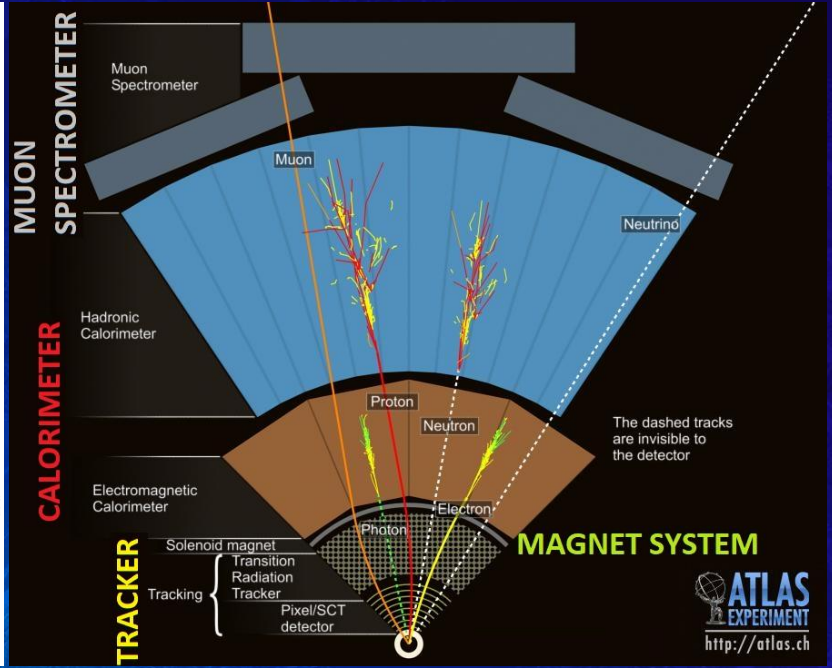

"Our work as "scanners" consisted of **identifying the trajectories of the particles** in the images taken inside the bubble chambers. [...] Initially, the work was done manually, using a pencil and a sheet of paper to note down the coordinates of where the interactions had taken place as one would on a map and a description of the interactions (the number of tracks, disintegration, ionisation, energy, etc.). Later, the measuring equipment evolved and was linked up to a computer.
**The data were recorded and immediately transmitted to be processed by a reconstruction programme** which would send back a message requesting a further set of measurements, corrections to be made or indicating that it had all the information it required. (Mandeline Znoy)

# 8. To modern particle detectors: particle identification & event reconstruction



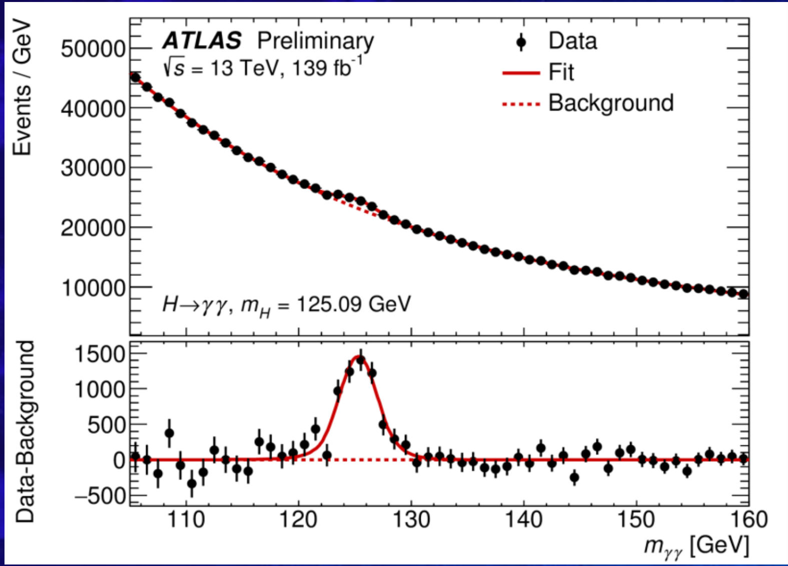

The ATLAS detector



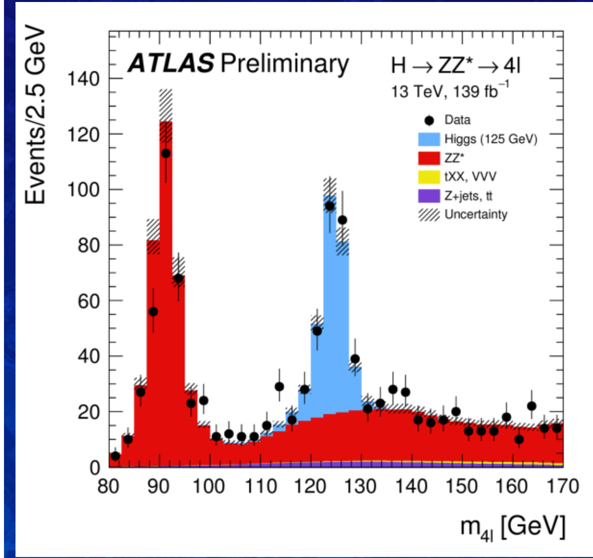

Event Cross Section in a computer generated image of the ATLAS detector

Joni Pham (CDM, University of Melbourne & ATLAS Collaboration)

# 9. Data analysis: understanding the physics, precision measurements & search




Higgs decays into 2 photons




Higgs decays into 4 leptons

When a particle decays and hence no longer exists, its mass before the decay can be calculated from the energies and momenta of the decay products. The inferred value of the mass is independent of the reference frame in which the energies and momenta are measured, so that that the mass called "invariant".

What we need: data, Monte Carlo simulation, background estimation, statistical & systematic uncertainty calculations.

# 10. Conclusion

- Particle Physics = seeing the invisibles from all the traces left behind (reconstruction + identification + data analysis). Data analysis principles & tools will be in the next lecture.

- Particle Physics offers a number of applications in everyday life, especially for medical field (radiation & non-radiation imaging, cancer diagnosis & treatment).